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LANDSAT FOLLOW-ON INVESTIGATION

No. 21300

Landsat Survey of Near-Shore Ice Conditions Along the Arctic Coast of Alaska

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ABSTRACT

Winter and spring near-shore ice conditions have been analyzed for the Beaufort Sea 1973-1977, and the Chukchi Sea 1973-1976. The chief objective of this analysis was to assess hazards related to activities associated with offshore petroleum developments.

Landsat imagery has been utilized to map major ice features related to regional ice morphology. Following this, significant features from individual Landsat image maps have been combined to yield regional maps of major ice ridge systems for each year of study and maps of flaw lead systems for representative seasons during each year of study. These regional maps have, in turn, been used to prepare seasonal ice morphology maps.

The seasonal ice morphology maps show, in terms of a zonal analysis, regions of statistically uniform ice behavior. The behavorial characteristics of each zone have been described in terms of coastal processes and bathymetric configuration.

Based on the combined seasonal morphologies, a zonal analysis of potential hazards related to offshore petroleum development has been made for the Chukchi and Beaufort seas. The hazards addressed are: safety of field personnel performing offshore geologic reconnaissance, large-scale displacement or deformation of fast ice sheet, the probability of formation of large ice ridge systems which could bring large forces to bear on offshore structures, and the possible fate of an under-ice oil spill.

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I. Introduction

A. Definition of the Problem

1. Exploratory and development pressures on nearshore areas. Environmental concerns stemming from the possibility of petroleum-related development on the Alaskan Continental Shelf have brought about great interest in Alaskan coastal processes. The distinctive feature of the arctic coasts of Alaska is that for a significant portion of the year these coastal waters are covered by ice. Clearly, an understanding of the dynamic morphology of ice in near shore areas is essential to an assessment of environmental and personnel risks imposed by offshore petroleum developments. The goal of this project has been to develop a synoptic picture of ice behavorial patterns along the Alaskan coast and to describe this morphology in such a way that the environmental and human risks can be identified.

Obviously the greatest ice-related influence on environmental hazards arising from petroleum development in ice-frequented waters arises from containment of petroleum under or within the ice. For this reason, it is necessary to develop a morphology of near shore ice characteristics and address this problem through those characteristics.

A second hazard related to ice, although not environmental, is the hazard personnel and equipment are subjected to when using ice as a platform in exploratory work. This risk can be evaluated through determination of persistence of ice sufficiently stable to act as an exploration platform.

The possibility of deposition of petroleum on the undersurface of arctic ice, its possible toxic effects and the ultimate fate of such a deposition should be considered. The problems involved include:

1) entrapment of light, water-soluable fractions of petroleum under the ice barrier with resulting prolonged high concentration of these known toxic agents,

2) difficulty in detection and delineation of the extent of the spill,

3) possible transport of petroleum beneath the ice or with ice during dynamic events, and

4) clean-up difficulties caused by combinations of 1 through 3 and possible danger to personnel and equipment during dynamic ice events.

2. <u>General ice conditions in near shore areas</u>

Ice conditions vary significantly depending on season and geographic location. Although the morphology presented later will be more complex, for the sake of this introduction two major zones of ice in near shore areas need be considered. These are:

1) The "fast ice zone", the area generally shoreward of the 20-meter isobath with quite stable ice much of the ice year. (December through June.)

2) The "shear zone", the area generally extending some distance beyond the 20-meter isobath. In this zone the ice potentially can undergo shear to the point of failure and move with respect to the fast ice at any time.

Within each zone the year can be broken into several behavioral periods. These are:

Month	Fast Zone Period	Shear Zone Period
Oct.	Freeze-up: Ice freezes in place or is driven into near shore areas and piled. Grounded ridges formed out to the 20-meter isobath. The result is a stable sheet of fast ice.	Freeze-up: Complex process with periods possibly including pack ice, new ice pans, open water, etc. Result is nearly complete covering of ocean with ice not stable and subject to motion.
Nov. Dec. Jan. Feb. Mar. Apr. May.	Stable: Ice within zone is stable with few leads resulting from shear. Cracks can occur resulting from temperature-related tension and tidal processes. Opening and closing of these cracks can cause micro-ridging. Ice grows in thickness approaching 3 meters by end of period.	Semi-stable: Static ice can extend several tens of km seaward beyond fast ice for several weeks at a time. Ice can fail in shear at any time. Shearing and refreezing: Ice more prone to shearing events and failure adjacent to edge of grounded ridges. However, after failure with cessation of motion, tendency for ice cover to be reestablished by freezing.
June July	Decay and break-up: Solar flux sufficiently great to initiate melting. Grounded ridges break up, fast ice melts close to shore, breaks up and melts farther offshore.	Close pack: successive shearing events break-up ice into pans of various size. Refreezing does not take place. Ice subject to significant displacement resulting from currents and winds.
Aug. Sept.	Ice Free: Area generally free of ice except for grounded remnants and blown-in pack ice.	Ice Free: Area generally free of ice except for blown-in pack ice and grounded features including ice islands.

3. Relevance of Ice Hazards to Operational Phases of Petroleum Industry

The relevance of ice-related environmental hazards to petroleum development should be considered in terms of four major phases of petroleum-related activities: Exploration I, Exploration II, Development and Production. Each of these phases has particular ice-related problems.

a. Exploration I. This activity is mainly geologic mapping by seismic crews. Currently seismic mapping is being carried out in the Beaufort Sea using fast ice as an operational platform rather than using boats during the relatively short and undependable open water season. Although few, if any, environmental hazards are created by this activity, hazards are imposed on the crews performing such work. The ice morphology developed here has been interpreted in terms of persistence of various ice zones and the period (if any) that exploration activities can be carried out from the ice within these zones.

b. Exploration II. During this phase, test wells are drilled--very likely from temporary structures including man-made gravel islands, anchored drill ships, movable platforms, etc. The choice of temporary structure used will depend in part on the morphological behavior of the ice in the location where a test well is desired. For instance, areas with a high incidence of hummock fields and shear ridging would be poor locations for anchored drill ships and might require artificial islands. A poor choice here might result in higher exploration costs and possibly environmental risk resulting from petroleum products spilled by damaged exploration equipment.

c. Development. During this phase, permanent structures are constructed for drilling of permanent wells and extraction facilities. Collector pipelines are laid and other permanent facilities are constructed. The considerations involved in the placement of these structures include the probability of ice piling around and upon man-made islands, ridge keel gouging of pipelines and also the effect of the facility on the morphology of near shore ice and this in turn on the quality and nature of habitats.

The information provided here will obviously yield information about ice piling and the probability of bottom plowing. Through the morphology of near shore ice including the dynamics of ice behavior near natural obstructions to ice motions, descriptive models of the impact of the creation of man-made islands on the morphology of near shore ice can be developed. This can then in turn be related to impact on near shore habitats.

d. Production. This phase of petroleum-related activities would take place over a span of many years. Consideration has to be given to the probability of adverse ice conditions over a period as long as twenty years and how these conditions relate to structures designed to support pumping and piping of crude petroleum. Within this period the greatest environmental hazards would arise from the possibility of a large oil spill. Because of the ice cover on the ocean most of the year, there is a great probability that a spill will become associated with the ice. In addition the presence of ice may even enhance the probability of a petroleum spill during the ice season. The ice morphology presented in this report has been interpreted in terms of the fate of an oil spill created at a time when it could become incorporated into the ice and at times when spilled oil would become trapped under the ice:

what transport might take place, how much spreading might occur, how long entrappment might last, and when release might occur. Also based on the morphology developed, consideration has been given to favorable locations for production facilities and to anticipation of techniques which may be used to deal with specific spills through prediction of the ice behavior to be expected within statistically-determined zones of uniform behavior of ice. Finally, consideration has been given to possible destruction of underwater facilities as a result of ocean-floor plowing by grounded sea ice features within each statistically-determined zone of uniform ice behavior.

B. Background

1. Geographic area. The area of this study includes the near shore regions of the Beaufort and Chukchi Seas, extending from Demarcation Point in the eastern Beaufort Sea to Nome on the south side of the Seward Peninsula. This area encompasses approximately 2500 kilometers of coastline, extending from approximately 141° to 169° west longitude and 64°30' to 71°30' north latitude. The coastline is irregular in shape, consisting of numerous bays, points, capes, and lagoons. The lagoons are bordered on the seaward side by long, narrow islands less than 4 meters elevation.

There is little human habitation in the region, especially along the Beaufort Sea coast. Nome, Kotzebue, Barrow, and Prudhoe Bay are the major population centers with populations of 3000, 4000, and 1000 respectively. There is one year-round native village with a population of approximately 200 along the Beaufort Sea coast east of Barrow, located in the Coleville Delta. The only permanent human habitations along this coast are three military Distant-Early-Warning stations at Lonely, Oliktok Point and Barter Island and the oil fields at Prudhoe Bay. However, there are several native villages along the coast between Barrow and Nome, most having populations less than 100 persons.

2. Physical setting. The bathymetry varies significantly in the area of study. In the Beaufort Sea the 80-meter isobath is approximately 70 kilometers offshore from Barrow to Demarcation Point and is the approximate edge of the continental shelf. The sea floor drops off very sharply from there to depths of 4000 meters.

The bathymetry of the Chukchi Sea is quite different from that of the Beaufort Sea. The maximum depth of the Chukchi Sea is approximately

70 meters. However, for most of the Beaufort and Chukchi Seas the bathymetry is not known accurately, especially the shelf areas of the Beaufort Sea.

The Pacific Gyre and the Bering Strait current are the major currents in the Beaufort and Chukchi Seas. The Pacific Gyre is a large clockwise flow of water that dominates the water currents in the Western Arctic Ocean. It results in an east-to-west flow of water in the Beaufort Sea. The Pacific Gyre does not directly affect the flow of water in the Chukchi Sea. The Chukchi currents are dominated by the northerly flow of water through the Bering Strait and into the Arctic Ocean.

The amount of tidal fluctuation varied significantly throughout the study area. At Point Barrow the range of the diurnal tide (the difference between mean higher high water and mean lower low water) is 12 centimeters (0.4 feet) along the entire Beaufort Sea coast from Barrow to Demarcation Point. However, the tides in the southern part of the Chukchi Sea are much greater; the diurnal range at Kiwalik in Kotzebue Sound is approximately 80 centimeters (2.7 feet) and at Nome is approximately 50 centimeters (1.7 feet). These are still relatively small fluctuations but they may measurably affect the ice conditions along the coast. The size of the tidal fluctuations is a function of the latitude; the tides generally decrease in size with increasing latitude.

The amount of daylight, i.e., the period from sunrise to sunset, undergoes large seasonal variations at high latitudes. At Barrow, the northern most point of land in this study, the sun does not set during the summer months from late May to late July, while the sun is below the horizon from approximately late November to late January. The conditions at Nome, the most southerly point in the study area, are similar although not as extreme.

3. <u>Climate</u>. The climatic conditions along the Beaufort Sea coast are relatively uniform from Barrow to Barter Island. The mean annual temperature at Barrow is -12.6°C with a record maximum of +26°C and a record minimum of -49°C. The normal yearly water equivalent precipitation at Barrow is 12.4 centimeters with an average yearly humidity of 80 percent. The mean yearly snowfall is 72.6 centimeters. The average windspeed at Barrow is 18.9 km/hr from the east; the maximum wind velocity was 93 km/hr from the west. The prevailing wind directions are from the east-northeast to east-southeast.

The weather conditions at Barter Island are similar to those at Barrow. The Barter Island mean annual temperature is -12°C with a maximum of +26°C and a record low of -51°C. The normal yearly water equivalent precipitation is 17.9 centimeters with a normal yearly snowfall of 113 centimeters. The humidity at Barter Island averages 80 percent. The average windspeed is 21.0 km/hr with a record maximum of 130 km/hr. The prevailing winds are from the west from January through April and from the east from May through December.

The climate along the Chukchi Sea coast from Barrow to Nome is warmer, wetter, and somewhat more variable than along the Beaufort Sea coast. The climatic conditions at Kotzebue are similar to those along the Beaufort coast. However, Kotzebue, being farther south, is somewhat warmer with a mean annual temperature of -6.2°C. The record maximum and minimum temperatures are +20°C and -47°C, respectively. Kotzebue receives slightly more precipitation than Barter Island, 22.3 cm water equivalent per year and 120 cm of snowfall per year. However, the humidity is slightly lower at Kotzebue, averaging 78 percent. The yearly average windspeed is 20.8 km/hr from the east with a maximum recorded windspeed

of 149 km/hr from the southeast. The prevailing winds are from the west from May through August and out of the east the remainder of the year.

Nome is on the Bering Sea side of the Seward Peninsula and therefore has weather somewhat different than that of the areas described above. The mean annual temperature at Nome is -5.1°C with a record high of +25°C and a record low of -39°C. The precipitation at Nome is nearly twice as great as at anywhere in the Chukchi or Beaufort Seas. The normal yearly water equivalent precipitation at Nome is 41.8 centimeters. However, the amount of snowfall is 137 centimeters, only slightly greater than at Barter Island and Kotzebue; a larger percentage of the precipitation occurs in the form of rain. Despite the higher precipitation, the average yearly humidity at Nome is 72 percent, considerably less than at Kotzebue or Barrow. The average windspeed at Nome is 17.3 km/hr from the north, off the hills of the Seward Peninsula. The maximum recorded windspeed at Nome was 88 km/hr from the southwest. Although the average yearly prevailing winds are from the north, the monthly averages are more variable. From December through March the winds are from the east, from the north April through May, from the west-southwest from June through August, and from September through November are again from the north.

II. Data Acquisition and Analysis

A. Selection of Scenes for Analysis

The primary sources of data for this study were Landsat I and Landsat II band-7 imagery. Landsat acquired images of the same 160 kilometer square area once every eighteen days. In the high latitudes of the Beaufort and Chukchi Seas, overlap of succeeding days' images of up to 80 percent occurs. In the Beaufort Sea, a given area may be imaged up to four days in a row. In the Chukchi Sea the overlap decreases with decreasing latitude so that in the Nome vicinity, an area will be imaged up to three days in a row. Twelve days' images are required for continuous coverage from Demarcation Point to Point Barrow. A minimum of six days' images are required to continuously cover the Chukchi Sea coast line from Point Barrow to Nome.

Each eighteen-day Landsat cycle was used as a data set. Depending on the availability of the images, several cycles of images were mapped for each year from 1973 through 1976 for the Chukchi Sea and 1973 through 1977 for the Beaufort Sea. Landsat does not obtain imagery from approximately mid-November to early February in the Beaufort and Chukchi Seas because the sun does not rise above the horizon at those latitudes during that time. Consequently, February is the earliest that images are available for these areas. Cycles of Landsat images were mapped for the following periods, depending on availability of images: (1) midwinter (mid-to-late February to early March); (2) late winter (mid-to-late March); (3) early spring (late March to late April); (4) late spring (May to mid-June); (5) summer (late June to mid-July); (6) late summer (late July to mid-August); and (7) late fall to early winter (late October to mid-November).

The choice of Landsat cycles used for this study depended primarily upon the cloud cover of the scenes of each cycle and the number of

images available. Some Landsat scenes were not available from NASA due to dense cloud cover. Other images with up to eighty percent cloud cover were obtained from NASA but not used. The usefulness of the images in a cycle was determined on an image-by-image basis. Two criteria were used. First, there needed to be enough coastline showing on the image to match a coastline overlay to the image. Generally, if even a small section of the coastline or coastal river was visible on the image, the image could be lined up with the overlay, using the latitude and longitude marks on the image. The latitude and longitude marks were not usable by themselves due to the difference in projections of the Landsat image and the Lambert conic conformal map overlay. The second criteria required that significant ice detail be visible through the cloud cover. "Significant" ice detail varied from scene to scene. For example, a low-contrast scene with moderate cloud cover but showing open leads in the ice has informational value whereas a scene with the same cloud conditions but not showing open leads may be useless for ice mapping. Generally, Landsat cycles with fewer than five usable scenes were not considered for detailed analysis. Exceptions included scenes used in stationary ice and open water maps (see below).

The Landsat cycles used in this study are shown in Figures II-1 through II-31 for the Beaufort Sea, and Figures II-32 through II-48 for the Chukchi Sea. The location, area and extent of each scene and the scene identification numbers are shown.

B. Mapping Technique

The images chosen for analysis were obtained at a scale of 1:500,000 from the EROS Data Center, Sioux Falls, South Dakota. The EROS Data Center produces 1:1,000,000 scale, 1:500,000 scale and 1:250,000

scale black and white prints of available Landsat imagery as standard products. The 1:1,000,000 scale images were too small to accurately map details while the 1:250,000 scale imagery was too expensive. Therefore, the 1:500,000 scale imagery was chosen as a compromise between cost and resolution of detail.

General overlays of the Beaufort Sea and Chukchi Sea coastlines including the major rivers were drawn in ink on clear acetate. The base maps used for the overlays were the 1:500,000 scale sectional aeronautical charts of Point Barrow, Cape Lisburne and Nome. These maps are published by the U.S. Department of Commerce using the Lambert conformal conic projection (standard parallels 49°20' and 54°40'). This projection is the closest to the Landsat projection found. The error in locating points on the Landsat image using the base map overlay is approximately a kilometer.

The technique used in mapping the ice on each Landsat image is as follows. First, the base map overlay was placed onto the image and the two were lined-up as closely as possible. Then a blank sheet of clear acetate was placed over the base map overlay. The coastline and rivers were drawn onto the blank acetate. Then the ice features were also drawn onto this acetate from the Landsat image. Finally, the bathymetry obtained from National Ocean Survey (formerly Coast and Geodetic Survey) nautical charts was drawn onto the map.

The initial interpretation was made using a blue-line copy of the acetate map. The distinguishable ice features, such as flaw leads, ridge systems, areas of smooth ice, etc., were identified primarily from Landsat image but other data (see below) were also used. The interpreted results were then transferred to a copy of the original acetate ice map

in the form of labeling nomenclature which was then reduced to page size (approximately 1,000,000 scale) for publication. These annotated ice maps of each Landsat image were the preliminary data products.

C. Creation of Composite Data Products

The preliminary ice maps of the individual Landsat scenes were used to create secondary, composite data products. The first generation of composite data products consisted of maps of edge of contiguous ice and of ridge systems for the Beaufort and Chukchi Seas.

A composite map showing the edge of contiguous ice, defined as the seaward boundary of the currently stationary ice was made for each Landsat cycle. The composite for each cycle was prepared by making a mosaic of the maps of the scenes in the cycles and outlining the contiguous ice edge. When the ice conditions were rapidly changing the significant changes in the edge of contiguous ice were observed from one day to the next, the edge of ice on the latest image was used in the composite map. The mosaic was then transferred to mylar, drawing in the contiguous ice edge, the 20-meter isobath, the coastline and the major rivers. Each composite map of contiguous ice edges contained either the data of all of the cycles for each year studied or the data for each season for all the years studied. Three seasons were differentiated, winter, early spring, and late spring - early summer. For the Chukchi Sea a map showing the average ice edge and the variation from the average was made for each season. From these, the averages of the three seasons were combined on one map to show the seasonal migration of the ice edge. All the above maps are discussed in Section IV of this report.

Yearly composite maps of the ridge systems visible on the Landsat imagery were made using the same method used for making the contiguous ice edge maps. One composite map was made for each ice year. Then all composite maps were compiled into one map of "all-time" ridge systems. These maps are discussed in Section IV.

The second generation of data products utilizing the preliminary and composite ice maps consists of ridge density maps, sea ice morphology maps and ice hazard maps for the Beaufort and Chukchi Seas. The ridge density maps were prepared from the all-time ridge system maps by visually delineating the areas of differing ridge density. The sea ice morphology maps were prepared from various sources including contiguous ice edge composite maps, ice ridge density maps and other data listed below. Morphology maps were prepared for the late fall to early winter ice season (approximately October to early March) and the midwinter to late spring ice season (approximately mid-March to late May - early June). The morphology maps contain information on the various ice conditions such as average edge of ice, fast ice, ridge occurrences, areas of smooth ice, fast-moving ice, hummock fields, etc. (see Section IV). The ice hazard maps used all of the above sources of data for determining the type and location of ice conditions that may be hazardous to offshore structures and ship traffic. The hazards include areas of heavy ridging, continuously changing ice conditions, ice islands, etc. The ice hazard maps are discussed in detail in Section IV of this report.

Other data products, compiled directly from Landsat imagery, included maps of stationary ice and open water for the Beaufort Sea. The term "stationary ice" as used here defines ice that was observed to have remained unmoved by wind and currents during breakup of the near shore

ice from one Landsat cycle to the next. Stationary ice is either grounded or attached to grounded ice. The stationary-ice maps were prepared by superimposing two images of the same location, but acquired at different times, on a viewing screen. The ice which had not moved during the time interval between the two images was mapped by placing a sheet of mylar over the viewing screen and tracing the outlines of the stationary ice onto the mylar. One such map was made for each year from 1973 through 1976 (see Section IV for the Beaufort Sea only). Due to lack of 1977 summer images, no 1977 stationary ice map was made.

The Beaufort open-water maps show the progressive increase in open water occurring in the near shore areas from the start of the melt season until the end of summer for the years 1973 through 1977. The open-water maps were prepared by overlaying a sheet of mylar on each Landsat image and tracing the outline of the extent of the open water. Data from all available imagery were used. The Beaufort Coastline was mapped in three sections for each year, showing the annual migration of the edge of the open water. The maps are discussed further in Section IV.

D. Ground Truth

This project has conducted numerous aerial reconnaissances along the Beaufort and Chukchi coasts with the objective of relating ice conditions and features with patterns observed on Landsat images. This effort was always placed at a disadvantage because of the six-week to two-month delay between Landsat data acquisition and the availability of hard copy imagery for reconnaissance purposes. Hence, only the most stable ice could be compared directly with imagery. In areas of unstable ice it was necessary to note and photograph ice conditions during the reconnaissance and wait two months for the comparison process. The difficulty with this was that nearly always the reconnaissance overlooked a feature of apparent significance on the Landsat imagery.

In general, it was found that while major ice features (for instance, ridge systems 50 m wide and 10 km long) can nearly always be identified on Landsat imagery, smaller features cannot be identified with any degree of regularity. The chief parameters here were found to be solar elevation angle, degree of snow cover and haze. It is not always apparent upon inspection of a single Landsat image that haze, for instance, is diminishing detectability of ice features. Often this only became apparent upon inspection of two overlapping images from successive days.

Perhaps the most useful ground truth information was obtained in June of 1974 when we obtained 1:20,000 scale panchromatic photography along a several hundred km flight line in the Beaufort Sea, followed a few days later by a NASA U-2 flight obtaining 1:120,000 scale color infrared photography and the acquisition of a good-quality Landsat image a few days later. On this data, it was possible to conclusively relate measurable ice features with patterns identified on Landsat imagery.

E. Applicability of Techniques Developed to Other Places Where Near Shore Ice is a Hazard.

The chief utility of Landsat data was found to be the detection of large ridge systems and lead openings by direct observation and observation of ice piling and shearing events largely by inference. The analysis of the ice hazards depends on the gathering of sufficient data to make possible the development of a synoptic picture of ice conditions. This, in turn, depends on two factors: the commitment of the spacecraft for data acquisition and a sufficiently adequate number of cloud and haze free occasions when data could be obtained.

Other than data availability two other factors need be considered: the nature of the hazard and the size of the area under consideration. The techniques used here have been developed to determine rather large zones of somewhat broad hazard description.

III. Results

A. Interpretation of Ice Maps

1. Selection of ice features pertinent to morphology. The individual maps of each Landsat scene were examined and annotated in terms of ice conditions observed on the sequence of images to which the individual image belonged. This exercise served to develop a historical perspective of ice behavior along that portion of coast. Descriptive histories, even with associated maps do not in themselves constitute a morphological description of ice behavior. In particular, the salient features of several year's ice dynamics must be compared to determine the patterns of ice behavior.

In order to accomplish this task, the maps which had been prepared were examined to find the mapped characteristics which could be compared from season-to-season and year-to-year.

One obvious class of characteristics found was large ridge systems. Ground truth exercises, described in section IID, had shown that maps based on Landsat imagery could be expected to show the locations of large ridge systems with a good degree of confidence.

A second class of characteristic found useful for development of a near shore ice morphology was the location of the seaward edge of contiguous ice. The term "contiguous ice" is used rather than "fast ice" because of the widespread useage of the term "fast ice" by various authors to describe a variety of conditions related to near shore ice. "Contiguous ice" means ice contiguous with the shore and continuous to the first break. Often the first break is the flaw lead. However, it could be the edge of open ocean or a polynya. For brevity these maps are labled "ice edge maps."

These two classes of features, recorded on as frequent a schedule as possible were found to be a suitable basis for formulating a near shore ice morphology related to hazardous conditions. Their utility is discussed in the next two sections.

2. Edge of contiguous ice. The edge of contiguous ice is often the boundary between "pack ice" and "shore fast ice." However, it should be realized that within a short period of time, the edge of contiguous ice can vary by tens of kilometers. This is particulary true off the Beaufort coast where the edge of contiguous ice has been observed to range from the 20-meter isobath to a point 30 to 40 km seaward. The cause of these extensions appears to be an absence of sufficient winds, currents and interval forces within the ice sheet to keep individual pans within the pack ice from freezing together. This condition can persist for several weeks before sufficient forces exist for failure to take place along lines considerably closer to shore.

When observing conditions similar to these, some observers define the "fast ice" as being defined by the ice called "contiguous" here. Others insist that the true "fast ice" is defined by the ice which would remain adjacent to shore after a major shearing event and subsequent failure of the ice sheet. Those who use the latter definition generally associate well-grounded ridge systems and other ice features with this stable edge of ice. Our results have shown sufficient exceptions to this association to cause us to not use this definition except in the most general sense and develop ice descriptions for each zone which can be identified to have uniform ice behavior.

3. <u>Ridge system maps</u>. Ridge system maps are useful in several ways leading to development of a near shore ice morphology. Ridges located within the existing contiguous ice sheet observed on the earliest available Landsat images each year, serve as a record of earlier, unobserved, ice event. Where they are grounded, ridges often--but not always--serve as anchoring points for the near shore ice sheet. By mapping ridges created for each year and comparing year-to-year it is possible to determine variability of dynamic ice events from one year to the next. Compilation of several years' ridge data onto one map shows the persistent locations of this type of feature, at the same time implying year-to-year persistence of the conditions responsible for ridge creation.

B. BEAUFORT SEA RESULTS

1. Contiguous Ice Edge Maps

a. Yearly Ice Edge Maps: For each year of study a single map has been prepared showing the edge of contiguous ice for each Landsat cycle yielding useful data. Throughout these maps it should be noted that generally the contiguous ice edge is not mapped for late spring. This is often because near shore flooding and melting occured, destroying the contiguous aspect of the near shore ice although vast areas remain in place. These vast areas of ice have been mapped under the heading; "stranded ice."

1). 1973 (Figure III-1)

i. 2-19 March Landsat cycle. During this time the edge of contiguous ice was quite far off shore. The individual Landsat image maps drawn for these dates merely indicate that the edge of ice is beyond their boundaries. This information is indicated here in terms of a series of lines indicating that the edge of ice was no closer to shore than these lines.

ii. 31 May--17 June. Where it could be identified the edge of contiguous ice has been mapped.

2). 1974 (Figure III-2)

i. 25 February--14 March. Shown by a dashed line, the edge of ice is never far from the 20-meter isobath except in the vicinity of Camden Bay. Compare this edge with the edge for 2-19 March the previous year.

ii. 15 March--3 April. Indicated by the dotted line, the edge of ice has remained very nearly constant except for the eastern Beaufort where it is now considerably closer to shore.

iii. 20 April--8 May. Indicated by alternating dots and dashes, contiguous ice was well off shore during this period and only the shoreward limit is shown here for much of the Beaufort Sea.

iv. 13-30 June. Shown by a line consisting of two dashes followed by a single dot, the edge of ice shows some agreement with earlier ice edges but also indications of the advanced season and decay of ice in Harrison Bay.

3). 1975 (Figure III-3)

i. 20 February--10 March. Only one good Landsat cycle was found for this year showing the edge of contiguous ice. During this time there is an indication that the edge of ice had been considerably farther off shore until just recently and was now nearly coincident with the 20-meter isobath for much of the Beaufort coast.

4). 1976 (Figure III-4)

i. 22 October--8 November. This ice edge, shown by a dashed line is the only extensive ice edge data obtained in the fall season during the entire study. It shows the edge of contiguous ice roughly coincident with the 20-meter isobath along the western Beaufort and significantly seaward of that line east of Harrison Bay.

ii. 6-23 February. This ice edge is indicated by a dotted line. For most of the Beaufort coast, the edge of contiguous ice is beyond the area mapped by the individual Landsat images. Only in the vicinity of Barrow is the actual ice edge mapped.

iii. 24-12 March. This ice edge is shown by a sequence of dots and dashes. For a good portion of the Beaufort coast this line is nearly parallel to the 20-meter isobath--tending however, to bridge over indentations in this contour.

iv. 31 March--17 April. The observed edge of contiguous ice for this date is shown by a line consisting of a dash followed by two dots. The data indicate that during this Landsat cycle the edge of contiguous ice moved considerably shoreward. The earlier images obtained in the eastern Beaufort show the edge of contiguous ice far off shore while the later images show the ice edge much closer to its normal position. Comparison of data obtained on March 12 and 14 show this to actually be the case in the central portion of the Beaufort Sea.

l). 1977 (Figure III-5)

i. 12 February--9 March. This Landsat cycle yielded ice edge data between February 26 and March 9 across the eastern and western portions of the Alaskan Beaufort Coast. It is interesting to note that except at Barrow, this ice edge is significantly seaward of the 20-meter isobath. It appears reasonably safe to assume that the ice edge for these dates extends across the unobserved area directly linking the two observed portions. At Barrow the ice edge does coincide with the 20-meter isobath.

ii. 9-26 March. Data indicates that the contiguous ice edge for these dates even further from shore than during the previous Landsat cycle with the exception of the Barrow vicinity where the ice edge is in the same location.

iii. 27 March--14 April. This Landsat cycle yielded data from Barter Island to eastern Harrison Bay and from Barrow eastward to Smith Bay. The eastern portion is considerably shoreward of previous ice edges and nearly coincides with the 20-meter isobath. Off Barrow the ice edge has remained coincident with the 20-meter isobath. However, to the east of Barrow, the edge of contiguous ice now curves around Point Barrow shoreward of the 20-fathom isobath to a location that remains constant throughout the ice year.

iv. 14 April--1 May. Data for this Landsat cycle begins opposite the Canning River and continues beyond Barrow. Now, the edge of contiguous ice is nearly coincident with the 20-meter isobath along the entire coast.

v. 2 May--30 June. The edge of contiguous ice was observed during this period across the central Beaufort coast. During this time it was again located significantly seaward of the 20-meter isobath.

vi. 25 June--15 July. Data for this Landsat cycle exists between July 6 and July 8. During this time the ice edge was observed off the Beaufort coast between the Canning and Colville Rivers. On July 7 the ice edge was again found far off shore. Shortly following that, on the 6th it was again located along the 20-meter isobath.

vii. 31 March--17 April. The observed edge of contiguous ice for this date is shown by a line conisting of a dash followed by two dots. The data indicate that during this Landsat cycle the edge of contiguous ice moved considerably shoreward. The earlier images obtained in the eastern Beaufort show the edge of contiguous ice far off shore while the later images show the ice edge much closer to its normal position. Comparison of data obtained on March 12 and 14 show this to actually be the case in the central portion of the Beaufort Sea.

b. Seasonal Ice Edge Maps: The data representing the various edges of contiguous ice have been recompiled for each season yielding sufficient information to warrant analysis: late winter (February-March), early spring (June-July) and late spring--early summer (June-July). The reason for these groupings is obvious; to determine whether each season can be characterized by a single, generalized ice edge representing that season. The results of this analysis will be discussed in order of season.

1). Late Winter Ice Edge. Data from the following Landsat cycles are utilized: 2-19 March 1973, 25 February--14 March 1974, 20 February--10 March 1975, 24 February--12 March 1976, and 19 February--9 March 1977. These ice edges, with the exception of the 1973 data show a good degree of similarity--running parallel and off shore from the 20-meter isobath, and bridging across landward indentations of the 20-meter isobath. The 1973 ice edge has been discussed previously--it was located very far off shore, well beyond the near shore area (Figure III-6).

2). <u>Early Spring Ice Edge</u>. Data from the following Landsat cycles were utilized: 15 March--3 April 1974, 31 March--17 April 1976, and 27 March--14 April 1977. The early spring ice edge is similar to the late winter ice edge. The most striking deviation is in the western Beaufort where the 1976 data show the ice edge closer to the 20-meter isobath than any other data--indicating that during early spring at least a degree of variability in ice edge in this region (Figure III-7).

3). <u>Late Spring--Early Summer Ice Edge</u>. The following Landsat cycles were utilized: 31 May--17 June 1973, 13-30 June 1974, and 17-30 June 1977. It is worth noting that the 31 May--17 June data coincide with the 20-meter isobath in the western Beaufort. This location is somewhat landward of the bulk of other ice edge data in this region but it does not represent a highly significant deviation. East of Harrison Bay the 1973 data strike significantly seaward. However, this is not considered to be a seasonal morphological feature; other data have shown that this phenomenon can occur in any season. What this does show, however, is that this can occur even this late in the ice season.

The mid-June 1974 data are the only ice edge information representing contiguous ice which show the decay of near shore ice to points will within the 20-meter isobath. This is only true for mid Harrison Bay to points westward. To the east of Harrison Bay the edge of contiguous ice is again located roughly along the 20-meter isobath (Figure III-8).

2. Ridge System Maps

a. Yearly Ridge System Maps: For each year of study a single map of the Beaufort coast has been prepared from the individual Landsat image maps showing the ridges observed during that year. No attempt has been made here to identify the date of formation of each ridge. The object of this mapping exercise was to identify those locations where ridging does occur in order to relate this phenomemon with bathymetric features including depth and isobath configuration. Mapping on a yearly basis was performed in order to provide information regarding year-to-year persistance in location and severity.

1). 1973 Ridge System Map: This map shows a cluster of major ridges offshore between Prudhoe Bay and Harrison Bay and a few ridges very close to shore in the western Canadian Beaufort. The ridges mapped well inside Harrison Bay are located in shallow waters and were very likely created at time of freeze-up (Figure III-9).

2). 1974 Ridge System Map: Here ridges were found throughout the length of the Beaufort coast. Of particular note are two prominent hummock fields in outer Harrison Bay where the complex of ridge ice have been represented by a series of dots covering the area of the hummock field. Also worthy of note is the fan-shaped focus of ridges centered on the headland just east of Camden Bay (Figure III-10).

3). 1975 Ridge System Map: Not many ridges were mapped for this year. However, in consistency with the previous two years, the greatest density of ridging occurs well offshore between Prudhoe and Harrison Bay (Figure III-11).

4). 1976 Ridge System Map: Again, as in 1974, major ridges were found throughout the length of the Beaufort coast. It is interesting to note these ridges are almost entirely located beyond the 20-meter isobath. This is a strong indication that these ridges were formed after early winter. Again, as in previous years, the greatest ridge density occurs offshore between Harrison and Prudhoe Bays. Again, the fan-shaped assembly of ridges occurs in Camden Bay (Figure III-12).

5). 1977 Ridge System Map: A larger volume of data was used in the compilation of the 1977 Ridge System Map than in previous maps. Not seen in previous years' data are the large number of ridges north of Camden Bay located 100 kilometers or more offshore. The area of hummocked ice can again be seen north of Harrison Bay. Generally, the pattern of ridging is the same as that observed in previous years (Figure III-13).

b. Composite Ridge System Map: This map shows the combined ridge systems for 1973, 1974, 1975, 1976 and 1977. Here ridge density trends noted on the yearly ridge maps become more clear (Figure III-14):

1). The greatest density along the Beaufort coast is found far offshore between Harrison and Prudhoe Bay.

2). A secondary maximum ridge density occurs in a fan-shaped pattern in eastern Camden Bay.

3). There is an indented area across inner Harrison Bay with a moderate tendency toward ridging.

4). A cluster of ridges occurs seaward of Midway and Cross Islands with a tendency toward greater density between the islands and the 20-meter isobath.

5). The focus of the fan-shaped ridge cluster in eastern Camden Bay is located significantly landward from the 20-meter isobath.

C. RIDGE DENSITY MAP: (Figure III-15) Using the composite Ridge Density Map as a guide, the near shore Beaufort Sea region has been delineated into regions of low to heavy ridge density. The ridge density map is then used when preparing maps of morphological ice behavior by combining information from several sources. It should be recognized that the ridge density map is based on several year's data and rather than predicting what density of ridging should be expected in any one year, should be thought of as showing the probability of ridging in any one year.

3. Stationary Ice Maps

a. Stationary vs. Contiguous Ice

During winter along the Beaufort Sea coast, large ridges form in a zone parallel to the shore. These ridges have keel depths sufficient to cause grounding out to approximately the 20-meter bathymetric contour. This zone of grounded ridges varies between a few kilometers and many tens of kilometers in width and effectively shields the smoother ice inshore from the effects of pack ice motion. The zone of immobile ice is usually referred to as the "fast ice zone."

When summer break up occurs, these grounded ridges are often the last ice forms to dislodge. These areas were not mapped in terms of edge of contiguous ice because they are not contiguous with the shore. Yet the ice does remain bottom fast and is an important part of the near shore ice regime. Three questions need to be answered regarding these stationary ice areas. 1) Where are these areas located? 2) Do they occur in the same locations each year? and 3) How long do they last in the summer?

b. Method of Analysis

The data base used in this study of stationary ice was Landsat band-7, 70 mm imagery projected onto a screen at 1:500,000 scale. The projection device used was an International Imaging Systems additive colorviewer. In order to determine which ice was stationary, two images taken at different times of the same area were projected simultaneously onto a screen. The two images were lined up by matching coastal features visible on both images. A transparent overlay with the coastline and major rivers drawn in was then laid on the screen. The areas where the ice had not moved were then traced onto the overlay.

c. Problems of Analysis

Images of the Beaufort Sea are not readily available in the mid and late summer because the area is often covered by clouds. As a consequence, only two or three sets of images for each year were available. This made repeat coverage from year to year not generally possible.

There were also problems determining which was stationary ice and which ice had moved. Because the margin of error due to the difference in projection of the Landsat image and the overlay maps was approximately 1 km, ice that appeared to move less than 1 km was generally considered to be stationary.

The time period between images was also important. Generally, if the images were one Landsat cycle (18 days) apart, the ice could be considered stationary if it had not moved. However, occasionally the only sequence of images available were only a day or two apart. Small drift rates during these times were difficult to observe.

d. Composite Stationary Ice Map (Figure III-16).

Four years' data were analyzed for stationary ice - 1973, 1974, 1975, and 1976. The data were combined on one map extending from Point Barrow to Herschel Island. The smallest stationary ice object plotted was approximately a kilometer in diameter. Analysis of this map shows that:

1). Stationary ice is generally located inshore of the 20-meter bathymetric contour. Inshore areas that are generally clear of stationary ice include the majority of Harrison Bay and the immediate river mouth vicinities.

2). Areas where stationary ice recurs were difficult to determine because of insufficient data. One area where it recurs and seems to last most of the summer is along the 20-meter contour north of the Colville River in Harrison Bay. Each year a large hummock field forms, causing a seaward bulge in the edge of the fast ice that persists until late summer. Another area where stationary ice was seen to recur was between Oliktok Point and the Sagavomirktok River, extending from shore to the 20-meter contour.

3). In 1976, stationary ice was last seen to exist on 2 August only in a small area west of Harrison Bay. The next image of the area was not obtained until 20 August (one Landsat cycle later). By then, the stationary ice had disappeared completely. Therefore, it can be concluded that stationary ice is generally gone by mid-August. One exception to this was seen in 1974. A large piece of a ridge system north of Oliktok point was observed to remain throughout the summer of 1974 and was still there in the spring of 1975. However, it did not remain as stationary ice in 1975.

4. Ice Island Observations and Frequency

a. Ice Islands - background

For approximately thirty years the existence of "ice islands" in the Arctic Ocean--particularly in the Pacific Gyre has been established. These features are tabular floes of freshwater ice ranging in size from dimensions on the order of km downwards. Their thickness can be as

great as 35 m. It has been reasonably well established that they originate from the Ellesmere Ice sheet. The number and size distribution of these features are not known. The Ellesmere Ice sheet does not calve continuously and it is possible that all existing ice islands were created in a small number of calving events. Ice islands ablate at the exposed surface and could be expected to possess a relatively long lifetime. However, there have been several observations of grounded ice islands along the Beaufort coast having broken into several pieces. Further, at least one large ice island has been observed to exit the gyre and enter the Atlantic Ocean.

Ice islands have been considered to constitute a threat to offshore facilities because their bulk is capable of obtaining a momentum many times greater than any conventional floe. For this reason it would be very useful to be able to develop statistical data representing their number, size distribution, and frequency of occurrence in nearshore Beaufort waters.

b. Results of Analysis of Imagery for Ice Island Data

Because of the potential value derived from determining statistical information concerning ice islands, each Landsat image used was examined explicitly for evidence of ice islands. It was thought that even if no ice islands could be observed directly, large ice islands would drift differentially from pack ice because of their deep draft and leave an identifiying wake in their trail.

Unfortunately, no ice islands were observed directly or indirectly on the Landsat imagery. On two occasions stranded and broken-up ice

islands were observed along the Beaufort coast during aerial reconnaissance operations. In both cases the broken-up island was approximately 300 m in diameter.

Attempts were made to identify these ice features on Landsat imagery. Positive identification could not be made in either case. In the first case, the ice island was observed well inside the contiguous ice between Admiralty and Smith Bays (1974). The exact position was difficult to determine however, because of rather poor navigation equipment on the aircraft used. The second ice island was observed during a 1976 photographic reconnaissance trip. It was located well by navigational equipment on board the aircraft and also by its location with respect to other ice features in the vicinity. Both grounded ice islands were located in water on the order of 20 m in depth. (These results are discussed in Section VC.)

C. Chukchi Sea Results

1. Contiguous Ice Edge Maps

a. Yearly Ice Edge Maps: For each year of study a single map has been prepared showing the edge of contiguous ice for each Landsat cycle yielding useful data.

1). 1973 (Figure III-17).

i. 2-19 March. Available data is shown by a dashed line. Later seasonal ice maps will show the ice edge data for this date to be rather unusual in the outer Kotzebue Sound region. Usually on this date the edge of contiguous ice is located well off

shore--bridging across the mouth of the Sound as far west as Shismaref. Here the edge of ice appears to cross the mouth at Cape Krusenstern. It should also be noted that between Point Hope and Cape Lisburne there is a portion of coast where the edge of contiguous ice coincides with the shore.

ii. 7-24 April. Available data is shown by a series of dots. Again as will be seen later, the edge of ice is considerably landward of its normal location in Kotzebue Sound during this period. Again, although in a slightly different location, the edge of contiguous ice coincides with the shore line in the vicinity of Cape Lisburne.

iii. 31 May-17 June. These data are shown by a line of dots and dashes. Note that by this time much of Kotzebue Sound is free of ice and several less protected areas are also free of ice.

2). 1974 (Figure III-18).

i. 25 February--14 March. Contiguous ice edge data for this date are shown as a series of dashes. Note how far out into outer Kotzebue Sound this ice edge is found, yet it nearly touches the shore south of Point Hope and again approaches the shore near Cape Lisburne. Beyond Cape Lisburne this ice edge remains far off shore until it reaches Cape Franklin.

ii. 2-19 April. Ice edge data for these dates are shown as a series of dots. Generally closer to shore, the ice edge for this date follows the shoreline configuration more closely than did the earlier ice edge. Note that at Cape Lisburne this ice edge does meet the coast.

iii. 26 May--12 June. Represented by alternating dots and dashes, the ice edge on this date is generally closer to shore than the dotted line representing the April ice edge. In some places, however, the contiguous ice edge even for this late date can be found seaward of the earlier edge--indicating that the edge of ice does not merely retreat with advancing season.

iv. 13-30 June. Contiguous ice edge data for this date are represented by a sequence consisting of two dots and a dash. Note that this ice edge is the most seaward of the four plotted for this year in the region just southeast of Point Hope. This ice is most likely pans which have been driven into this location and compacted somewhat. Farther north, the ice edge for this date can be seen to be quite close to shore except at Pt. Franklin where the April ice edge was actually closer to shore.

3). 1975. Note the unusually close similarity between the ice edges shown for this year (Figure III-19).

i. 20 February--9 March. Data for this period are represented by a series of dashes. Again, as in previous years, this earliest ice edge extends farthest seaward in outer Kotzebue Sound and off Cape Lisburne.

ii. 28 March--14 April. The contiguous ice edge for this Landsat cycle is indicated by a line of two dots followed by two dashes. Note that north of Wales, the edge of contiguous ice now extends farther seaward then previously. This occurred as a result of s-ridge build-up of a large hummock field in this location. This ice

edge becomes adjacent to the coast south of Point Hope--as do all other ice edges for this year. (None was recorded for late June as was shown for the previous year.) This ice edge also coincides with the coast at Cape Lisburne as March ice edges have done in previous years.

iii. 6-23 April. Ice edge data for this date are shown by a series of dots. This ice edge is similar to the previous ice edge except on the exposed sides of the Seward Peninsula and Cape Lisburne. In both cases the ice edge now extends considerably farther seaward.

iv. 30 May--16 June. Data are shown for this date by a dot-dash sequence. Where these data were available they did not differ greatly from the previous ice edge data.

4). <u>1976</u> (Figure III-20).

i. 6-23 February. Shown by a dashed line, this ice edge differs significantly from other winter ice edges which have been mapped for this period: This ice edge indents far into Kotzebue Sound while previously for this date the edge of ice has been far seaward, well into outer Kotzebue Sound.

ii. 24 February--12 March. Shown by a dot-dash sequence, this ice edge appears similar to ice edges drawn for the same date on previous years. Note that at Cape Lisburne it indicates no ice adjacent to the coast for a considerable distance. To the north, this ice edge generally resembles ice edges drawn for previous years during this period.

iii. 14-31 March. These ice edge data are shown by a sequence of two dots followed by two dashes. While this ice edge resembles others for this period in the vicinity of the Seward Peninsula and Kotzebue Sound it differs somewhat to the north where it is unusually distant from the shore in the vicinity of Cape Thompson and Cape Lisburne. Farther north, between Icy Cape and Pt. Franklin this ice edge advances unusually far seaward followed by a rapid coastward motion. North of Pt. Franklin this behavior is repeated somewhat.

iv. 19 April--6 May. Shown by a series of dots, the contiguous ice edge data for this date are as unusual as the data shown for 6-23 February: Here, instead of indenting toward and into Kotzebue Sound, this ice edge actually bridges across out Kotzebue Sound. It would seem that the winter and spring data were interchanged. Farther to the north, the springtime data continues to exhibit this unusual behavior--remaining far seaward.

b. Seasonal Composite Maps

1). Late Winter. Shown here are the ice edge data for late winter (February-March) Landsat cycles, 1973 through 1976. These data indicate some interesting trends showing areas tending toward a high degree of variability in ice edge location. While one might expect a focusing of ice edge locations at exposed headlands (Wales, Point Hope, Cape Lisburne, Pt. Franklin, and Barrow), Pt. Lay is not similarly exposed but yet the ice edge data there also exhibit this behavior pattern (Figure III-21).

2). Mid-Spring. Shown here are the ice edge data for mid-spring (April-May) Landsat cycles, 1973 through 1976. Again as with the late winter data there are zones of great location stability and other areas with a high degree of variability. Generally while there appears to be a greater overall uniformity of ice edge location here, less stability is indicated off Point Hope and Point Lay (Figure III-22).

3). Late Spring--Early Summer. Shown here are the ice edge data for late spring and early summer (May-June) 1973 through 1976. These data show that in some regions (Kotzebue Sound, for instance) there can be a high degree of variability at this time while other locations exhibit a tendency toward more uniform ice edge behavior. Because of the absence of data from each year in some locations, some indicated trends--particularly those toward uniformity should not be considered as particularly strong (Figure III-23).

c. Average Seasonal Ice Edges

The composite maps of section b have been analyzed to produce a single average ice edge for each season. In addition, the greatest and least bounds of observed ice edge have also been shown in order to document the reliability of the average ice edge for use in morphological modeling and hazard analysis.

1). Late Winter. The average ice edge for February-March passes close to shore at Bering Strait and proceeds toward Kotzebue Sound at a great distance from shore, bridging across the mouth of outer Kotzebue Sound. North of Kotzebue Sound, the average edge is consider-

ably closer to shore than south of the Sound, finally passing just a few km off Pt. Hope and Cape Lisburne. North of Cape Lisburne the average ice edge follows the coastline at some distance until reaching Pt. Franklin, where again the average edge is quite close to shore. The average edge bridges across the coastal indentation between Pt. Franklin and Barrow, passing that point at a distance of approximately 10 km (Figure III-24).

2). Mid-Spring. The average ice edge for this period does not differ a great deal from the average ice edge for late winter except for a tendency to lie closer to shore in some locations. It is interesting to note that the envelope of greatest and least bounds is much smaller during this season than during late winter--indicating perhaps a steady-state condition during this period. However, the variability in outer Kotzebue Sound is still quite large during this season (Figure III-25).

3). Late Spring--Early Summer. The average ice edge for this season is generally closer to shore than the previous season's average ice edge. The envelope of maximum and minimum contiguous ice edge loactions during this period is generally narrow except for the vicinities of large embayments. For instance, in Kotzebue Sound the envelope is large just as it has been in other seasons--only now it is located even farther inshore (Figure III-26).

d. Migration of Average Seasonal Edge of Contiguous Ice

This map shows the three seasonal average ice edges described in section c plotted together so that the possibility of a systematic change in ice edge location can be investigated. When considering the

relationship between these ice edges, the envelope of maximum and minimum ice edge location must be borne in mind. For instance, both in Kotzebue Sound and north of Cape Lisburne, there is a wide seasonal spatial variation in average ice edge location and the immediate conclusion might well be to consider any apparent seasonal motion of ice edge more significant than opposite Icy Cape where the spatial variation is smaller. However, in Kotzebue Sound the variation envelopes are all quite large so that seasonal average ice edges located relatively close together (late winter and mid-spring for instance) do not indicate a significant variation. North of Cape Lisburne the envelopes are generally small so that some credibility may be given to the mid-spring ice edge being found more seaward then the late winter ice edge. At Icy Cape the variation envelopes are small so that despite the proximity of the average ice edges the seasonal progression shown may have statistical significance.

Bearing these qualifications in mind the following observations can be made from this map (Figure III-27).

1). At Wales, Point Thompson, Point Hope, Cape Lisburne, and Point Franklin there are at least small stretches of coast where the average ice edge remains at the same distance from shore throughout the three seasons. The mechanisms responsible for the agreement of these average ice edges will be discussed in the development of the Chukchi coastal morphology. It should be noted that at Wales, Point Hope, and Cape Lisburne and Point Franklin the variation envelopes

are fairly large indicating that the ice edge varies in location during each season. The agreement in average location at Pt. Thompson between each season indicates that no seasonal trend is to be found in the varying location of ice edge here.

2). North of Cape Lisburne there are significant reaches of coast where the sequence of average ice edge distance from shore varies uniformly with season. That is, late winter is furthest from shore, mid-spring is intermediate, and late spring--early summer is closest to shore.

3). Immediately north of both the Seward Peninsula and Cape Lisburne the ice edge sequence for winter and spring is reversed.

4). The winter and spring sequence are reversed in Kotzebue Sound. However, this trend would not appear if the 6-23 February 1976 data were removed from the late winter data set. This could only be done if some valid justification can be found. The data here should be taken to indicate a high degree of variability of contiguous ice edge in this zone.

d. Chukchi Sea Ice Ridge Systems

1). Yearly Ridge System. These maps show locations of ridge systems which could be recognized on Landsat imagery clearly as ridge systems. The ridges identified are generally s-ridges which are several km long.

i. 1973. Ridges were mapped in only a few locations this year. It is interesting to note that they were found in locations adjacent to headlands in all cases. These headlands were: the tip of the Seward Peninsula at Wales, Point Lay and Point Franklin (Figure III-28).

ii. 1974. The ridge pattern mapped for 1974 is significantly different from the 1973 pattern. There appears to be a tendency for ridges to be located on the south side of major embayments. The large "V" shaped ridge northeast of Cape Lisburne was formed when ice was driven southward toward the coast. It is interesting to note that although the forces creating this ridge system were compressional the ridges formed under shear failure (Figure III-29).

iii. 1975. Ridge systems mapped for 1975 were even fewer than previous years. No particular pattern was observed. In the embayment between Barrow and Pt. Franklin a ridge was observed to follow the coast in a way resembling the pattern found between Point Franklin and Icy Cape the previous year. Off Cape Lisburne a long ridge system was found in a position indicating flow of ice across Cape Lisburne. Ridges in this location were not seen previously (Figure III-30).

iv. 1976. Three ridge systems were observed this year north of Bering Strait. They have an interesting similarity in that they all lie "north" of the three major headlands; Seward Peninsula, Cape Lisburne, and Icy Cape (Figure III-31).

2). Ridge System Composite (Figure III-32)

All ridge systems observed and discussed previously are plotted together on this map. There are two objects of this exercise: The first is to indicate where, over a long time period, ridging occurs. The second is to determine whether, when seen together, the individual yearly ridging patterns fit into a single morphological pattern.

The first objective is reflected in the general morphological and hazard maps produced where long term average behavior is under consideration. The second objective will help determine the year-to-year reliability of the morphological picture developed. Under this second category we should note upon examing the ridge systems drawn for each year that the following behavorial patterns emerge:

i. Generally, the 1976 ridges are the most seaward in all locations.

ii. The 1973 ridges are the most landward in all locations .

Nevertheless,

i. All the ridges north of the Seward Peninsula form a single pattern as do the ridges off Pt. Lay and Icy Cape and the ridges south of Barrow indicating that although they occurred in different years, they represent a single morphological pattern.

ii. The possible exception to this uniformity is found at Cape Lisburne where three year's data appear to indicate three distinct patterns.

The general over-all pattern which emerges is that of streamlining along the coast from Barrow to Point Lay with an abrupt seaward shift at that location to a new flowing pattern across the tip of Cape Lisburne followed by a similar pattern across the tip of the Seward Peninsula.

IV. Conclusions

A. Beaufort Sea

In this section, the results described in Section III are interpreted in terms of seasonal morphologies of the Beaufort Sea near shore ice regime. Then, based on these morphologies, an assessment of relative hazards has been made for the Beaufort nearshore area.

The development of a complete near shore morphology should be based on an analysis of statistical data from several years where average conditions and deviations from average conditions have been determined, followed by detailed analysis of specific individual events to test the validity of the conclusions drawn on the basis of the statistical analysis. In the Beaufort Sea five years' statistical data has been compiled and related to specific ice events observed during the period of study. Rather than being considered a completed product, this analysis should be considered a starting point for further study.

The ice year has been broken into two periods: Late fall to early winter, and mid-winter to late spring. A map has been prepared for each season showing areas of relatively uniform behavioral characteristics which can then be described for each area. These two periods include the times when ice hazards appear to be greatest. The division was based on splitting the period of formation of the most stable ice from the later period when this ice is essentially static.

1. Beaufort Sea Near Shore Ice Morphology

a. Late fall to Early Winter Morphology: This period includes the time of freeze-up to the establishment of stable ice within the nearshore area. This period roughly corresponds to early November

through late January. Unfortunately, very few direct observations of ice conditions during this period are availab!e; in late fall cloudy conditions prevail and between late November and early February no Landsat data is normally obtained because solar depression angles less than 6° generally do not provide good imagery. However, this project was able to arrange with NASA to obtain imagery at solar depression angles down to 0° during fall, 1976. These images were found quite useful even at 0° solar elevation angle.

Other than interpretation of the few fall images which were obtained, the construction of the late fall-early winter morphology was based largely upon inference from later imagery and observation of processes occurring at other times. This morphology is presented in the form of a map of the Beaufort Sea nearshore area showing areas having statistically uniform morphology conditions. These conditions are described in the legend to the map (Figure IV-1).

Legend - Late Fall to Early Winter Morphology Map

I. This zone contains generally smooth ice located in water less than 10 meters deep. This ice is often formed in place but it can consist of floes of recently formed ice rafted into location and surrounded by a matrix of younger ice. In the latter case, roughness is not uncommon, espcially around the rims of these floes. Leads have often been opened in this area and subsequently frozen over, providing long, broad avenues of smooth ice. These frozen-over leads have often been subjected to compressive forces which have formed pressure ridges within them. The ice within this zone is completely formed by early January; it would be very unusual for lead openings, other than tidal or tension cracks, to occur after this date.

Shear ridging appears to be at a minimum within this zone, principally because sufficient anchoring mechanisms occur at the edge of this zone, causing stress concentration at outer locations. Because of their large draft, multiyear floes do not penetrate into this zone but tend to pile up along the 10-meter isobath where they ground and become anchors for ice located shoreward.

IIa-h. These areas are the active shear zone as soon as the anchoring floes are established along the 10-meter isobath. S-ridges form within this zone, adding strength to the newly formed ice sheet. The sheet quickly builds seaward through growth of new ice, attachment of floes, construction of new ridges and grounding of multiyear floes. The dashed line represents the mean seaward boundary of this activity. However, it should be recognized that

in the absence of disturbance, ice contiguous with the shore can extend over 100 km. seaward, remaining in place for weeks at a time. On the other hand, until the ice in this zone is well stabilized, leads can open and ridging or shear deformation can take place at almost any location within it.

Pack ice motion is usually from east to west. When forces act to cause compression along the line of contact between moving and stationary ice, s-ridges are formed. This ridging activity appears to be greater in some areas than in others. Details of ridging activity are given in the following subsections.

IIa. This rather large area strectching from Cape Halkett to Barrow has rather low ridging activity, although lead formation appears to be rather frequent. This would suggest a relative absence of compressive forces along this portion of the coast.

IIb. Moderate ridging occurs in this area early in the ice year as a result of ice being driven into Harrison Bay from the east. This activity soon ceases as a result of the increased strength created in the ice. Thereafter, coastal ice motions are deflected along zone llc.

IIc. This zone of moderate ridging is created after the increased strength of ice in zone llb halts motions into Harrison Bay from the east. Because of shoals just shoreward of the 20-meter isobath, large draft multiyear floes act as anchoring mechanisms for the sheet of ice to the shoreward (Zone III). Ridges created in this zone during early winter have a high probability of remaining in place the entire ice year.

IId. This zone of high ridging frequency begins approximately at the 20-meter isobath and extends seaward to the vicinity of the 40-meter isobath. Ridges in this zone are not well grounded and can be severed by lead formation. However, following such an event, there is a high probability of new s-ridge formation along the boundary of the opened lead. All along this zone, from Mikkelson Bay to a point off Cape Halkett, long highly identifiable s-ridges can be formed by the combination of motion of pack ice toward the west and by compressive forces as it is held against the fast ice.

IIe. This is a zone of moderate ridge formation extending from the west side of Camden Bay to Mikkelson Bay. It is presumed that, although westward slippage of seaward ice takes place here similar to Zones llc and lld, compressive forces are not as great along this section of coast. As a result, s-ridging is less pronounced.

IIf. This is a zone of high ridging frequency formed largely by compression of pack ice against fast ice as the ice moves either east or west. The compression is created when the moving pack ice encounters ice held fast against the large headland in this vicinity. Note that the zone of high ridging frequency extends considerably shoreward of the 20-meter isobath. It is of interest to note that the prevailing wind at Barter Island shifts from east in November to west in December, returning to east in January and then back to west in February. Hence, these ridges could be created by ice motion in either direction.

IIg. This area has a low frequency of ridging. One possible explanation for this phenomena is that when winds are from the east, if ice motion in this vicinity takes place, it simply fails in tension and pulls away from the shore with the result that no

compressive components exists to form large s-ridges. If, on the other hand, the wind is from the east, the ice piles in compression here and fails in shear to the north, forming Zone IIf. The compression piles are not as visible as s-ridges hence the area is mapped as having a low frequency of ridging.

IIh. Ridging frequency is increased in this zone as a result of the shoreline being more nearly parallel to the direction of ice motion with the result that east winds can cause creation of s-ridges.

IIi. This is an area of low ridging frequency in the middle of outer Harrison Bay. It apparently forms because shoals to the seaward cause grounding of multiyear ice features and pressure ridges. As a consequence large s-ridges form to the seaward of the shoals, providing additional protection.

b. Mid-winter to Late Spring Morphology: The morphology of nearshore ice during this period has been determined by direct observation through Landsat imagery. Many areas with considerable ice activity during the previous period are now static with very little chance of violent deformation. However, tension and tidal cracks appear and "work" as conditions change. Other areas are now static and have very little chance of major failure resulting in s-ridging but have been observed to develop crack patterns suggesting failure under shear. In general, during this period the active edge of ice often moves further from shore than the 60-meter isobath and then returns to that vicinity during dynamic ice events.

The morphology of nearshore ice during this period has been summarized in map form (Figure IV-2). Based on the statistical data, zones have been delineated which can be described in terms of a uniform ice behavorial pattern within each zone. The behavorial patterns have been described in the following legend.

Legend - Mid-Winter to Late Spring Morphology Map

I. Stable fast ice. The ice within this classification is usually well formed by the beginning of February. With one possible exception (denoted Ib), the ice in this category is sufficiently stable that flaw leads form to the seaward throughout this period (somewhere within category II). Hence, except for opening and closing of tidal and tension cracks, the ice within this zone is static during this period. The following subdivisions within this zone are based on statistical occurrence of major ridges.

Ia. Zone of light ridging. Generally overlying shallow waters, this ice is free from major ridges. Often large expanses of very smooth ice can be found.

Ib. Zone of moderate ridging. A variety of conditions can be encountered reflecting conditions during time of freeze-up. Multi-year floes may be encased in a matrix of new ice. Large floes of worked, first year ice may be broken by smooth, frozen-over lead systems. Pressure ridging can be expected in these areas. There is also a moderate probability of encountering an S-ridge created some time during freeze-up.

Ic. Zone of intermediate ridging. Ice conditions are similar to those described for zone Id. However, the probability of large S-ridges is considerably increased.

Id. Zone of severe ridging. The ice in these areas is likely to be first year pack ice and multiyear floes - obviously not formed in their present location. A great deal of ridging and pressuring has taken place, creating large grounded hummock fields in some areas. Note that these areas occur along the seaward

boundary of stable fast ice and often at points of inflection of this boundary. These areas are the main anchors of the fast ice system.

II. Zone of mid-winter - late spring flaw lead formation. The areas within this classification are prone to flaw lead formation at any time during this period. Following flaw lead formation, S-ridging may occur, the lead may freeze over and remain static for weeks at a time, the recently frozen lead may close, creating S- and P-ridges, or the leads may open yet again. However, it is also possible to have an extensive sheet of stable, unbroken fast ice for long periods of time within this zone. Flaw lead formation probability is low at the shoreward boundary of this zone, increases seaward to a maximum probability, then begins to decrease further from shore. The variability of ridge density is the major criterion for the subdivisions within the zone.

IIa. Zone of moderate ridging with a high probability of flaw lead formation. Ice behavior is related more to the Chukchi Sea morphology than to the Beaufort Sea.

IIb Zone of relatively low ridging probability, but prone to flaw lead and polynya formation during this period.

IIc. Zone of moderate ridging, prone to flaw lead formation during this period.

IId. Zone of intermediate ridging, prone to flaw lead formation.

IIe. Zone of flaw lead formation with greatest probability of ridge formation. Very often long S-ridges can be observed running the length of this zone.

IIf. Zone of flaw lead formation with intermediate ridge formation frequency.

IIg. Zone of low probability of flaw lead formation with moderate probability of major ridge formation. (Flaw leads are more likely to be formed shoreward of this zone).

IIh. Zone of flaw lead formation with moderate ridge probability.

IIi. Zone of flaw lead formation with low ridge probability.

IIj. Zone of low probability of flaw lead formation with low ridge probability

III. Generally zone of pack ice. Usually a flaw lead or recently active flaw lead (currently thinly frozen over) can be found between this zone and zone I. P-ridging is a frequent phenomenon in this zone and S-ridging can occur but the probability is much lower than in the II zones.

2. Hazards Resulting From Beaufort Sea Ice Morphology

Based on the Beaufort Sea seasonal morphologies, an assessment of relative hazard during the several phases of offshore petroleum development has been made. The hazards identified are, of course, related only to those aspects of the general over-all ice morphologies identified here. These hazards include: 1) The relative safety of field crews operating on the ice, 2) Possible ice motion endangering drilling operations from temporary structures (anchored drill ships, ice structures, pile structures, etc.), 3) The probability of ice piling events posing obstruction to rapid surface evacuation from potentially hazardous situations, 4) The potential for ice piling events and subsequent damage to under sea structures from the subsurface structure of the piled ice, and 5) The potential for increased bearing load against bottom-founded structure as a result of piled ice.

Figure IV-3 shows the Beaufort coast with several major hazard zones delineated. The hazard zones have been chosen on the basis of a rather uniform hazard potential within each zone. The zones have been grouped into 5 major zones based largely on probability of ice edge occurrence and subdivided further largely on the basis of ridging probability. In the caption for Figure IV-3 each major zone is described followed by descriptions of the subzones.

Caption - Beaufort Sea Ice Hazard Map

I. This zone represents the most stable ice along the Beaufort coast. After December it is extremely safe for surface travel, (with one possible exception noted later) it has not been observed to fail in shear between December and June (therefore deformations are generally small), and ice piling is at a minimum.

Actually, this zone contains two subzones not shown here determined almost entirely by depth of water. The first subzone consists of water less than two meters in depth. The significance of this zone is that by late winter, the ocean freezes to this depth hence after that date this subzone should be very stable. The second subzone consists of the balance of Zone I and contains depths as great as 10 meters. These two subzones have not been differentiated because the relative hazard between the two has not been considered extremely great.

The greatest source of hazard observed to occur in this zone was the mid-winter formation of thermal tension cracks. These cracks occur generally during very cold temperatures in December and open to a width of 2 to 3 m. Often the new ice formed in the crack is drifted over with snow with the result that it does not equal the thickness of the surrounding ice. On one occasion in Prudhoe Bay a large piece of equipment and its driver were lost when an attempt was made to merely drive across a frozen-over tension crack. There appears to be some repetition from year-to-year of these cracks; one major tension crack appears between Thetis Island and Oliktok Point annually.

Ridging occurs within this zone only early within the ice season with the participating floes generally on the order of 30-40 cm in thickness. Major ocean floor plowing should not be expected from these events. After December and January the active edge of ice is well seaward of this zone. No ice failure events have been observed to occur which indicate deformation within this zone between the end of January and the end of May. It is estimated that an event resulting in 20 m deformation would have been observable by the techniques utilized here.

II. Like Zone I, this zone consists of stable fast ice during late winter and early spring. However, the relative hazards related to this zone are somewhat greater than those related to Zone I. During the five year observation period reported here, failure to the point of large scale displacement (10 km) was not observed within this zone.

The zone has been subdivided generally in terms of ridge density although not entirely with respect to that attribute. Generally the zone is safe for surface travel during winter and spring. Structures are subjected to varying amounts of ridging, and varying amounts of displacement can take place. However, this is still within the zone of "stable fast ice" generally held in place by grounded ice features along its seaward edges. Oil spilled under this zone should encounter a relatively smooth undersurface and might spread significantly. This process would be aided by lunar and barometric pumping of water in the confines between the ocean floor and bottom of the ice.

IIa. This zone is adjacent to Zone I and parallels the coast from Barrow to Barter Island. Its chief distinction from Zone I is that within it there is a greater ridging density. During winter and spring few hazards should be encountered by surface operations. The probability of deformation in this zone is greater than in Zone I. During the five-year observation period reported here, failure under apparent shear was observed on only a few occasions within this zone. The failure resulted in crack formation in a stress release pattern with displacements on the order of a kilometer. Complete failure accompanied by s-ridge or lead formation was observed on one occasion and has led to the distinction between Zones IIa and IIb. The probability of lead formation is low and the probability of encountering major obstructions during an attempt to escape lead-forming events is not extremely great.

This zone does contain the shallow areas just seaward of the Barrier Islands, however, and is often seaward of the 10-meter isobath, although generally contained by the 20-meter isobath. The ridge density was observed to be greater than in Zone I and consequently ice piling events by older and thicker ice than in Zone I are likely.

Oil spilled in this zone would encounter a somewhat rough under ice surface and therefore would spread less than in Zone I. Clean-up operations, however, would be hampered by the ice surface roughness.

IIb. This has been designated a separate hazard area from Zone IIa because of one lead-forming event occurring along the dotted line distinguishing these two zones. It is interesting to note that were Zone IIb not recognized, this would be the only significant area in Zone IIa seaward of the 20-meter isobath. However, the one lead-forming event observed indicates that this area is not as stable as the balance of Zone IIa and should be distinguished. Within this zone then, there is greater hazard to surface parties through the possibility of ice failure.

IIc. This is an area of relatively smooth ice surrounded by ice which is statistically rougher in terms of major ridge systems. It has often been found to contain floes of varying ages surrounded by younger ice. Generally, however, both are annual ice. This has been determined to be a zone of relatively low hazard to surface travel. Dynamic ice events appear to be at a local minimum. Deformation and lead formation has not been observed during winter and spring. Oil spilled under this ice might spread but could well be channeled by the smooth undersurface of the newer ice surrounding the older floes.

IId. and IIe. These are areas of heavy and moderate ridging respectively, located inshore from the average location of flaw leads. Although ridging occurs here, these areas are quite stable and often contain large areas of grounded ridge systems. The chief hazard to personnel performing surface operations comes from the probability of lead formation, compounded by the difficulty imposed on attempts at

rapid escape by the great surface roughness. Clearly in late fall massive ridge-forming events occur here and at least once, an ice island fragment was observed grounded in this vicinity. It would appear, then, that structures placed in these zones could bear the load of ice piled from several meters above the sea surface all the way to the ocean floor.

Oil spilled under this surface would most likely become trapped in many deep pools located between ridge keels and as a result spread less than in other areas.

IIf. This is a large zone of moderate ridging located largely inshore from the average edge of winter and spring contiguous ice. Hazards to crews performing surface operations vary somewhat depending on proximity to the average location of flaw leads where there is the greatest chance of deformation or lead opening. One arm of this zone extends well into inner Harrison Bay where surface conditions are more stable than at the zones' seaward edge. Some deformation and accompanying displacement has been observed in this region during winter and spring. However, the ice has not been observed to the point of creation of an edge of contiguous ice through flaw lead formation.

Structures placed in this region could be confronted with massive ice piles and, in fact, large hummock fields have been observed in this zone. Oil spilled under this zone would encounter fairly significant resistance to its spreading as a result of the under surface roughness of this zone.

IIg. This is a zone of severe ridging located shoreward of the shoreward limit of the observed envelope of flaw leads. Located northwest of Cross Island, it is often the site of massive s-ridges formed in November and early December. Many of these ridges are apparently well-grounded and remain in place well into summer. Cracks have been observed here in mid-winter, but the ice has not failed to the point of major lead formation and followed by displacement along the lead.

Surface operations in this area would involve an element of risk related to the chance of lead formation and the relative impediment to surface travel presented by the ice surface. Structures could very well have massive ice piles adjacent to them and available to exert relatively large forces against them.

An oil spill would tend to pool under this ice and have its spread thus retarded.

IIh. This zone is the east end of an area of severe ridging. This portion lies shoreward of the flaw lead zone. Hazards in this zone are essentially the same as those described for Zone IIg.

IIi. This is a rather large zone of moderate ridge density lying shoreward of the shoreward edge of winter and spring contiguous ice. In two places this zone is shoreward of areas of more severe ridging between it and the shoreward edge of contiguous ice while a large area actually borders this edge. A good portion of this zone lies seaward of the 20-meter isobath. This circumstance might raise a question concerning the stability of that portion. Cer-

Oil spilled under this ice could be expected to pool somewhat because of the moderately rough undersurface.

An additional hazard in this subzone not encountered by other subzones in the II group is the possibility of ice island occurrences because of the large area with water depths greater than 20 meters.

IIj. This is a zone of severe ridging located shoreward of the flaw lead zone. Because this zone lies seaward of the 20-meter isobath, its stability should be held in question. However, the flaw lead has consistently been observed along its seaward edge. Hence, while surface operations might be performed, precautions should be made to make certain that evacuation could be made quickly.

Structures placed in this zone would not only be endangered by the possibility of major ridge-building events but also by the possibility of ice island transects across the zone during open water and freeze-up periods.

An under ice oil spill located here would probably not spread greatly as a result of the enhanced underwater topography.

IIk. This is a zone of moderate ridging lying to the east of Barter Island. Like Zone IIj, much of this zone lies seaward of the 20-meter isobath. Hazards described for this zone are essentially the same as those described for IIj except that the probability of a major ridge confronting a structure is diminished and the pooling effect of an underwater oil spill is similarly decreased.

III. This major zone is defined by the statistical envelope of observed flaw leads. During mid-winter flaw leads quickly freeze over after formation while during late spring they tend to freeze much more slowly and as a result remain active much longer. During the mid-winter periods when the Beaufort flaw lead has frozen in this vicinity, a vast area seaward of this area is often constituted of contiguous ice. The term "flaw lead" looses its significance during this period. However, when a flaw lead does appear it has the greatest probability of occurring within Zone III.

Hazards in Zone III are significantly greater than in Zone II because of the flaw lead probability and because this zone lies almost entirely seaward of the 20-meter isobath making visits of ice islands and other deep-draft ice features very possible. Under ice oil spills located within this zone face a high probability of exposure to the water surface through the creation of flaw leads.

It should be noted that whereas Zone II could be thought of as having a good probability of remaining static throughout winter and spring, with the result that large ridge probabilities could be thought of as indicating stability through grounding and consequent anchoring of ice, a high ridge probability in this region indicates a high probability of instability through flaw lead formation and ridge-building events.

Major ice displacements are possible in this zone at any time associated with lead-formating events and ice deformation. <u>This possibility is found throughout this zone and should be kept in mind in terms of the subzones defined below</u>.

IIIa. This zone rounds Pt. Barrow joining the Beaufort and Chukchi Seas. It represents an area of moderate ridging and a very narrow focus of flaw lead location. It should be considered extremely hazardous for surface operations. Structures placed in this zone would be confronted by almost constant ridge-building events. An oil spill located here would be pooled significantly by the ice bottom topography but would also face a high probability of exposure to the water surface and incorporation within the ice over a large area through lead and ridge activity.

IIIb. This is an area of high probability of flaw lead formation with a low probability of ridging. During winter and spring there is often new ice being formed in this vicinity. It should be considered extremely hazardous for surface operations. Structures placed in this zone may very well have a high probability of escaping major ridge-building events. However, their interaction with the often newly-created ice within this zone should be considered carefully. Further, the probability of ice island visits may be enhanced by coastal configuration here. Oil spilled within this zone would have a high probability of incorporation into new ice and transport with pack ice motion.

IIIc. This is a large area of low probability of major ridging oriented parallel to the coast and located far beyond the 20-meter isobath. It should be considered significantly hazardous for surface operations. A structure placed in this zone would have a low probability of encountering a major ridging event but ice

island visits would be quite possible. Oil spilled under this zone would not be pooled by major ridges and would have a large probability of incorporation into the pack ice through lead formation.

IIId. This zone runs parallel to the coast for much of the length of the Alaskan Beaufort Sea. It possesses a moderate probability of ridge building events, few impediments to ice island visits and a good chance of being located seaward of the flaw lead. For these reasons the zone should be considered hazardous for each of the activities considered here under "hazards".

IIIe. This is a relatively small zone of moderate probability of major ridging located inshore of Zone IIIf (described next) possessing a high probability of major ridging. It is generally somewhat stable but flaw leads have cut across it. Presuming suitable precautions are taken, surface operations could be performed in this zone. Structures placed here could well be confronted by by major ridge-building events while there is a small probability that because of the bathometric configuration, some protection from ice island visits may be afforded. Oil spilled under this zone would very likely be pooled by the bottomside ice configuration.

IIIf. This is a large zone of great probability of major ridging running parallel to the coast from Harrison Bay to Flaxman Island. This zone also has a great probability of containing the flaw lead. And, because it is largely located over waters deeper than 20 meters, there is a good chance of an ice island visit.

Surface operations in this zone should be considered fairly hazardous due to the compounding effect of great ridge density and probability of lead formation events. Structures placed in this zone would be subject to major ridge-building events and at least the potential for ice island visits. Oil spilled under this zone would very likely be pooled significantly by the underside configuration of the ice. However, there would also be a great probability of near future oil incorporation into ice piles through lead formation and ridge-creating events.

IIIg. This is a narrow zone of light ridging located beyond Zone IIId. The hazards related to this zone are essentially the same as the hazards in Zone IIId except that the probability of flaw lead formation between this zone and shore is even greater, and the possibility of an ice island visit is enhanced while the probability of major ridging is decreased.

IIIh. This is a zone of low probability of major ridge building events but with little obstruction to ice island visits. The probability of a flaw lead formation between a point located in this zone and shore is very great. During lead-forming events there is a good chance that field crews could flee dangerous situations to nearby points but not escape to shore by surface transportation. Structures, while largely free from major ridge-building events could very well be confronted by ice islands. An under ice oil spill would probably spread significantly and soon be introduced into the pack ice.

IIIj. This zone possesses a low ridging probability and a high probability that flaw leads are located to the shoreward. Hazards are essentially the same as Zone IIIh.

IV. This zone contains ice with a moderate probability of major ridge formation as a result of ice interaction with the shore, yet there is a high probability that flaw leads will be found shoreward of this zone. Because of the shore-linked aspect of its morphology and hazards, it has been differentiated from Zone V which is essentially pack ice.

Surface operations in this zone should not be performed without provisions for non-surface evacuation. Structures placed in this zone will be subject to at least a finite probability of major ridge formation, while ice island and floeberg visitations are entirely possible. Oil spilled under this zone would tend to be pooled significantly by major ridges but be subject to introduction to the ocean surface during lead-forming events.

V. This zone is essentially the pack ice zone. Here, influence of shore on ice morphology and hazards has been reduced to regional influences. In the region north of the Beaufort Sea there are periods of stable ice extending up to six weeks duration. During that time, field operations could be carried out here subject to the provision for non-surface evacuation if necessary. However, the relative danger is actually diminished from that in Zones III and IV because of the smaller chance for major shear deformation in this zone. It is very unlikely structures will ever be placed in this zone. An under ice oil spill would essentially be a spill into pack ice.

B. Chukchi Sea

In this section, the results described in Section III are interpreted in terms of seasonal morphologies of the Chukchi Sea near shore ice regime. Then based on these morphologies, an assessment of relative hazards has been made for the Chukchi nearshore area.

1. Chukchi Sea Morphology

The ice year has been broken into three periods: mid-winter, early spring and late spring. The morphology of the Chukchi Sea ice is much more dynamic than the Beaufort Sea morphology. While the Beaufort Sea exhibits a vast area of static ice with an occasional much larger area attached, there is an almost constantly active flaw lead along the Chukchi coast with new ice being formed, detached, piled, and transported almost constantly. For that reason the morphology of Chukchi ice has been described in a somewhat different way from the morphology of Beaufort Sea ice.

Figures IV-3, IV-4 and IV-5 contain the morphological description of Chukchi Sea ice behavior. Two fundamental ice features have been utilized to construct these maps: The edge of contiguous ice which essentially coincides with the flaw lead, and large massive ridge systems. In some respects these two ice features are independent of one another; the edge of contiguous ice is, in general, controlled by season--being farther off shore during winter and advancing toward shore with advancing season while the location of large ridge systems appears to be controlled mainly by bathymetric configuration.

Because of this relative independence, the major influence or change in the near shore morphology will be seen to be the changing

location of the edge of contiguous ice. Lest this seem an over simplification of the near shore morphological processes, it should be pointed out that at some places a direct relationship has been noted. In particular, north of Bering Strait s-ridges have been observed to build seaward extending the edge of contiguous ice in that direction while elsewhere the edge of contiguous ice is retreating toward shore.

The Chukchi Sea Ice Morphology Maps have a much different appearance than do the Beaufort Sea Maps. One major reason for this is the opportunity for ice to move out Bering Strait. All during the late winter and spring period, ice moving events take place along the Chukchi coast, often creating shear ridges along shoals jutting seaward from the string of capes and headlands which are so prominent along the coast. Increasingly as one travels to the south, the edge of contiguous ice between headlands is more poorly defined and the ice contained is more prone to seaward motion leaving areas of open water behind. In general, there is often a lead system extending the length of the coast from Barrow to Cape Lisburne.

Just south of Cape Lisburne and north of Point Hope is an area with a constantly reformed polynya.

South of Point Hope the effect of ice motion out Bering Strait is even more prominent. Another recurring polynya occurs just southeast of Point Hope formed by southward ice motion. Kotzebue Sound is generally covered by stable ice during much of the ice year, but the presence of a zone of weak and often moving ice just seaward hints that this sheet of ice is probably potentially unstable.

At the southern end of the Chukchi Sea is Bering Strait. Just north of the Strait is a large system of shoals where large extensive shear ridges can be built during ice motion out the Strait.

2. Hazards Resulting From Chukchi Sea Morphology

Based on the Chukchi Sea morphology described in the previous section, the question of hazards related to offshore petroleum development has been addressed. Map IV-7 shows a number of hazard descriptor areas having sufficiently uniform conditions within each area that a hazard description could be written for each area.

The hazards addressed include: the safety of crews and equipment used to perform surface exploratory operations, an assessment of the possible load-bearing ice surface imposed on structures resulting from ice piling events, the possible plowing of the ocean floor by ice piling events, and the possible fate of petroleum spilled in each descriptor area.

The following table describes the hazards related to each of the descriptor areas defined on map IV-7.

CHUKCHI SEA ICE HAZARDS

Zone	Description of Hazards

1. This is an area generally safe for travel from January through early June. Depending on conditions at freeze-up, ice seaward of the islands can vary from smooth to very rough. In front of Barrow, this zone narrows to a strip 200 m wide.

   This is not an area of major ridging and surface structures would be subjected to a minimum of hazards resulting from ice piling or keel plowing of the ocean floor.

   Fall and early winter oil spills could be transported away or incorporated into permanent ice. From early winter till breakup, under ice spills would remain trapped except for transport through occasional tension and tidal cracks.

2. An area of moderate ridging formed early in the ice year, this area is generally safe for surface travel from January through early June. Chances of seaward lead formation increase with the advance of the season. There is also moderate hazard to structures resulting from ice piling and keel plowing.

   Fall and early winter oil spills are very likely to be transported away with ice motion. Later spills are likely to be trapped under the ice and pooled between ridge keels until spring when thawing and breakup of the ice would cause lead pumping and transport of the oil.

3. An area of moderate ridging formed early in the ice year is subject to lead formation with low probability from January through March. Lead formation is very likely after that date. Surface travel is least hazardous during January through March and moderately hazardous at other times. Because of dynamic ice events in this region, this area should not be considered for the location of camps.

Surface and subsurface structures are subject to damage by moderate ridging and keel plowing of the sea ice at almost any time during the ice year.

Oil spills would be subject to transport or incorporation into piled ice at any time during the ice season. The longest period during which an oil spill would not be subject to ice motion is on the order of two to three weeks.

4. This is an area subject to moderate ridging activity at any time during the ice season. Since lead formation is frequent during the ice season as well, surface travel is extremely dangerous at any time and is actually less hazardous farther offshore.

Surface and subsurface structures are subject to damage by ice piling and plowing during the entire ice season.

Oil spilled in this region during the ice season would soon become subject to lead pumping and incorporation into ice piles and ridges. There would be a high probability of transport within one week of the spill. Clean-up attempts would be made difficult by the possibility of ice motion.

5. An area of severe ridging seaward of the normal edge of stable ice at any time during the ice season, this is an extremely hazardous area for exploration activities. In addition, surface structures would be constantly subjected to piling events and damage by ice keel plowing.

Oil spilled in this region would very likely be incorporated into piled ice, pumped onto the surface by lead activity and incorporated into newly-forming ice within leads.

6. An area of severe ridging just shoreward of the mid-winter edge of fast ice, this region should not be considered stable. However, during mid-winter, ice here might remain in place two to three weeks at a time. By mid-spring, the boundary of fast ice is located along the shoreward edge of this zone.

The safety of surface operations in this zone is similar to that of Zone 4 except that the increased ridging in Zone 6 would make retreats to safer ice more difficult in case of dangerous ice conditions, and the increased piling in this area increases the probability of parties being caught in truly hazardous situations. Camps should not be established in this area.

Surface and subsurface structures would be subjected to damage by great amounts of ice piling and plowing --- perhaps as severe as any place along the Beaufort/Chukchi coast.

Oil spills generally would be located under mobile ice subject to piling events most of the ice year. However, during mid-winter spills might be trapped under stationary ice for as long as six weeks. Lead formation is a possibility at any time during the ice year.

7. This is an area of severe ridging just offshore from the springtime edge of stable ice. It is generally stable from mid-winter to mid-spring. But because the configuration of Point Barrow exposes ice to the possibility of occasional dynamic ridging events, even this area should be considered hazardous for prolonged surface activity. (See description of Zone 6). The hazards associated with this zone are similar to Zone 6 except that there is a longer period - up to two to three months - when the ice may not be subject to motion.

8. This area is subject to severe ridging offshore of the late spring edge of contiguous ice yet inshore of the early spring edge of stable ice. The ridges in this zone are formed early in the ice year and generally remain in place until the melt season. Surface exploration activities are not extremely hazardous. However, because of the wide variation in location of the springtime edge of fast ice, the relative safety of this zone is not as great as its counterpart along the Beaufort coast.

Surface and subsurface structures would be subject to damage by ridging and plowing events generally only at the beginning (November-December) and end (June-July) of the ice season.

Oil spills in this zone during November and December could be transported away with near shore ice motion or incorporated into ice piles in the near shore area (within this zone or even inshore of this zone). From December until early June, an under-ice oil

spill would most likely remain trapped under the ice in this area. After June sufficient leads and cracks exist that the oil could be pumped to the surface by ice activity.

9. An area of moderate ridging formed early in the ice year, this area is located offshore of the late spring ice edge but inshore of the early spring ice edge. This zone is similar to Zone 2 on the other side of Barrow in terms of hazard, and is generally safe for surface travel from January through June. Chances of seaward lead formation increase with the advance of the ice season. Moderate hazard to structures exist resulting from ice piling and ice keel plowing.

Fall and early winter oil spills would probably be transported away with any ice motion. Later spills are likely to be trapped under the ice and pooled between ridge keels until spring.

10. This is an area generally free from major ridges running from south of Barrow to near Pt. Franklin and is located seaward of the late spring ice edge but shoreward of the early spring ice edge. Because of the great statistical variation of the ice edge in this region, the description of this area and Zone 11 should not be considered entirely accurate. One reason for the wide variation of behavior here is the location of these areas in waters considerably deeper than 20 meters, and hence, the absence of significant grounded ice features to provide anchoring mechanisms for fast ice. This situation is reversed on headlands (Pt. Barrow, Pt. Franklin, Icy Cape, etc.) where many of the identified near shore zones are located within the 20-meter isobath.

This area tends to be free of lead activity from mid-winter until mid-spring. However, surface travel should be considered hazardous even at those times because of the wide variation in behavior mentioned above.

Surface and subsurface structures are relatively free from hazards due to major piling and plowing events. Subsurface oil spills may be pooled under stationary ice for up to a month at a time but lead activity and ice motion would eventually result in the pools of oil breaking up and being redistributed.

11. This area, generally free from major ridges, runs from south of Pt. Barrow to north of Pt. Franklin and is located seaward of the early spring ice edge but shoreward of the mid-winter ice edge. Because of the reasons described for Zone 10, the boundaries of this zone are not well defined. The hazards described for Zone 10 also apply to this zone. However, the probability of stationary ice here is even less than in Zone 10 and the possibility is generally restricted to the period December-February.

12. This is a broad zone subject to moderate ridging running from Barrow to Pt. Franklin and located shoreward of the late spring ice edge. Although this is a generally stable zone with some grounded ice features, the relative hazard to surface travel increases as one progresses seaward. Some lead activity has occurred here during winter months although, statistically, this area is considered stable from December through late June.

Under-ice oil spills would be trapped under generally stable ice from December through June with a low probability of transport or major pumping onto the surface by lead activity.

Surface and subsurface structures would be subjected to hazards due to moderate ice piling and plowing events early (November-December) and late (June-July) in the ice season.

13. This zone of ice extends from shore to the area of moderate ridging and is entirely within the late spring edge of ice, being wide in areas of embayment and narrow across headlands. Although this zone extends along the entire coast it has been divided into smaller zones because some characteristics of the ice change from place to place.

Ice topography in this zone is dependent on conditions at the time of final freeze-up, which usually has occurred by the end of December. The ice surface topography will vary from location to location and from year-to-year. The surface can at times be sufficiently smooth for the operation of wheeled vehicles. At other times it consists of a jumbled pile of small plates of ice about 30 cm thick and 2-3 m across presenting a major obstacle for even foot travel. Ridging generally does not occur in this zone and, in fact, usually forms the seaward boundary of this zone.

Structures placed in this zone would be subject to relatively hazardous conditions due to piling and plowing. By the end of the ice year most first year ice is on the order of 2 m thick and as a result considerable expanses of the ice in this zone will be frozen

to and into the bottom. This is particularly true in lagoon areas such as Pt. Franklin. Because of this and the long life of the ice zone, under-ice oil spills could spread considerable distances along this zone.

14. This zone adjacent to Pt. Franklin appears to exhibit ice behavioral characteristics somewhat different from ice zones adjacent to other headlands. Very little ridging appears to occur here and the edge of contiguous ice varies little from season to season. This behavior appears to be explained by the fact that the ocean floor profile drops off rapidly to 20 meters along this section of coast and the same profile is maintained much of the length of this region. Hence, ridging resulting from differential motion under compression ("shear ridging") is confined to a very narrow zone and may not be of sufficient extent to be observable on a Landsat image. This zone may be quite narrow and consist of a single shear ridge perhaps 50 m wide.

Obviously this zone is hazardous for surface travel because of the high degree of activity within it and structures would be endangered by the constant ice motion.

15. This is a broad zone of moderate ridging located seaward of the late spring edge of contiguous ice but shoreward of the mid-winter ice edge. The statistical variation of the edge of this zone is relatively small, hence, the boundaries of this zone should be considered fairly well defined.

Surface travel in this zone should be relatively safe from December through late March, with increasing risk toward the seaward side. Structures placed here would be exposed to moderate

ridging before December and after March. Underwater oil spills would be contained under the ice from December through March and subject to transport at other times.

16. This is a zone of moderate ridging inshore of the late spring edge of ice and located between Pt. Franklin and Icy Cape. This zone is generally stable from December through late March and could be used for surface exploration with a reasonable degree of safety during this period. Structures are subject to ice motion, piling and plowing before December and after April. Under-ice oil spills could be expected to be trapped under the ice.

17. This is a continuation of Zones 13 and 1. Though this zone may be free of ridging, the surface can vary considerably from place-to-place and from year-to-year. (See description of Zone 13).

18. This zone of relatively stable ice between December and February has a high probability of spatial variation. It is located off Icy Cape and seaward of a zone of moderate ridging. While from time-to-time stable contiguous ice exists here, its suitability for surface travel is very poor. It is subject to being broken off at almost any time to join the adjacent pack ice.

This area is subject to ice motions at any time during the ice year with stable ice perhaps two weeks at a time between December and March.

Oil spills under this region would soon be introduced into the pack ice.

19. This is an area of severe ridging located between the early spring and late spring boundaries of contiguous ice. This zone lying off Icy Cape is located over Blossom Shoals with water depths on the order of six meters. Early in the ice year ice grounds on these shoals and remains stranded until the edge of contiguous ice migrates across the shoals with the advance of the ice season. This particular zone includes the stranded piled ice which is broken free between March and May-June.

Under normal conditions surface travel on this zone would be relatively safe between late December and May. Obviously structures located here would be subjected to severe ice piling events during November and December, but after that time structures would be insulated from piling events.

Oil spilled under this region would be trapped under the ice between December and May and would very likely be pooled in many small chambers beneath the piled ice.

The variation in boundary location of this zone is on the order of half the width of the zone itself. Hence while the zone is statistically meaningful the precise position of the zone can vary on the order of its own width.

20. This zone is a region of severe ridging located inshore of the late spring edge of fast ice. This zone is similar to Zone 19. In terms of hazards, the hazard to surface travel in this zone is considerably less than in Zone 19 although during most years the ridging might make travel difficult.

21,22. This is a region of moderate ridging with an adjacent zone of severe ridging located between the mid-winter and early spring edges of ice. This is an active area during the entire ice year with perhaps the exception of a few weeks between December and March. However, the statistical variation of the location of these zones is sufficiently large so that their precise positions cannot be reliably determined. Also, depending on ice activity, ridges created in these two areas may be broken away to drift with the pack ice.

Generally, these two areas are extremely hazardous for surface travel. Also, structures located within these zones would be subjected to nearly constant piling and plowing except for perhaps one or two periods of several weeks in mid-winter.

Oil spilled under these two regions would soon be transported into the pack ice.

23. A zone of moderate ridging located between the early spring and late spring edges of fast ice, this zone is similar to the adjacent Zone 19 except for ridge density (see description of Zone 19).

24. A zone of mid-winter contiguous ice extending from Icy Cape to Point Lay, this zone lies between the mid-winter and early spring edges of fast ice. However, along this section of the coast the variation of the mid-winter edge of ice is large and the width of this region can vary considerably. For this reason, the existence of this zone should not be depended upon for surface travel.

Structures located in this region would generally be free from ice piling and plowing events. Oil leaked under this area would soon be transported into the pack ice region.

25. This is a zone of reasonably stable contiguous ice located between the early and late spring boundaries of contiguous ice. The statistical variation of the positions of these boundaries is on the order of the width of the zone and hence, its width and precise location can vary from year-to-year. The ice within this zone is generally relatively smooth and free from major ridges. It is formed during early winter (November-December) and is broken up by late spring (April-May).

This area is moderately safe for surface travel in mid-winter with decreasing safety toward the seaward boundary. Structures in general would not be subject to major piling and plowing although this section of coast should not be considered entirely free from ridging activity. Subsurface oil spills within this zone would generally remain trapped between December and April-May and, because of the lack of ridged ice in this area, might spread considerable distances beneath the ice.

26. This zone is composed of generally ridge-free ice located inshore from the late spring edge of ice and is actually an extension of Zones 13 and 17 farther to the north. However, it widens out in this vicinity and has a somewhat different morphology than Zones 13 and 17.

This zone consists of two sub-zones: ice within the barrier islands and ice outside the barrier islands. Within the barrier islands the ice is essentially lagoon ice. It is generally formed early (November) in the ice year and often melts earlier than ice just seaward of the barrier islands. It is ridge-free but often has working tension and tidal cracks, and in areas less than two meters deep, it is often frozen to the bottom. Because of these characteristics, structures are subject to a minimum of piling and plowing while under water oil spills would remain in place under the ice for great lengths of time, working to the surface through the tension and tidal cracks. Obviously surface travel in this portion of Zone 26 is quite safe until the ice melts or overflows with melt water.

The portion of Zone 26 outside the barrier islands is generally ridge-free and remains in place until May-June. The statistical variation of its outer boundary is quite large and hence the exact width of this zone measured from the barrier islands will vary from year-to-year. This zone is formed early in the ice year and is generally free of major ridges. Lead activity does not occur until late spring (May-June). The area is generally safe for surface travel with hazard increasing significantly after early spring and with distance from shore. Structures placed in this zone would be subjected to relatively small ridging and plowing events. However, it is very likely that one or more small shear ridges may become frozen into the zone during its time of formation. Oil spilled under this zone is likely to remain until May or June.

27. This is a zone of moderate ridging located between the early and late spring edges of ice. The early and late spring edges of ice converge along this section of coast off Pt. Lay while the mid-winter edge of ice remains much farther offshore. Also, the shoreward statistical variation of the mid-winter edge of ice is quite broad here, generally coinciding with the combined edge of early and late spring fast ice. This small zone is reasonably safe for surface travel until early spring but increasingly hazardous after that time. Structures would be exposed to a moderate amount of ridging and plowing. Underwater oil spills would most likely be trapped under ice here until mid-spring when lead-forming activity would introduce the oil into the pack ice.

28. This zone of moderate ridging is located inshore from the combined early and late spring edges of fast ice. (See description for Zone 27.) This zone is formed during November and December and usually lasts until mid-spring. Early and late spring data show that variations in the boundaries of this zone can cause it to be very narrow with flow leads quite close to shore.

This area should be safe for surface travel from December through early March but with increasing probability of lead formation following that date. Structures placed in this zone are exposed to ice piling and plowing events during November and December. Oil spilled under the surface in this zone would normally remain in place until May when it would be introduced into the pack ice due to breakup of the ice.

29. This is a zone of moderate ridging just seaward of the combined edge of early and late spring contiguous ice. This zone is subject to lead formation generally after early March but the data show that lead formation has occurred at earlier dates. For this reason, surface travel in this area is somewhat dangerous between December and March and increasingly so after that date. The relative danger of surface travel is increased by the occurrence of moderate ridging in the area making rapid travel away from developing hazards difficult.

Structures placed in this area are subject to damage due to ice piling and plowing at nearly all times during the ice season. Oil leaked under this area would be introduced into the pack ice through lead opening activity.

30. This zone of generally ridge-free ice is located inshore from the late spring edge of ice and extends from Pt. Lay to Cape Lisburne. This zone is actually an extension of Zone 26 but is much broader and has a somewhat different morphology. Occasionally, ridge-building events can occur within this zone (see Zone 36) but long shear ridges are probably unusual.

This zone should be relatively safe for surface travel between December and April-May except that during severe conditions ice piling can occur within the area. Structures placed in this area would be relatively free from ice piling events and bottom plowing appears to be at a minimum. Under-ice oil spills would normally be trapped under the ice between December and April.

31, 32. These are zones of moderate and severe ridging resulting from motion of ice past Cape Lisburne. Both are located seaward of the mid-winter edge of fast ice and, therefore, not part of the near shore regime. However, these zones have been included in this analysis to help explain the morphology of the near shore ice.

33. This zone of moderate ridging is located between the mid-winter and early spring edges of fast ice. The variation in width of this zone is on the order of the width of the zone, and therefore, even between mid-winter and early spring the stability of fast ice in this area is uncertain. Therefore, this area is only marginaly safe for surface travel. Examination of individual cases shows that the flaw lead is often located within this zone.

Because of water depths in this zone, it is unlikely that structures attached to the bottom would be constructed. However, it appears that any structure located within this area would rarely be free from ice motion for more than two to three weeks. Similarly, oil leaked under the ice in this zone would soon be incorporated into the moving pack ice.

34. This two-part zone of ice, relatively free from ridging is located between the early and late spring edges of contiguous ice. The zone is broken into two subzones by Zone 35. Examination of the statistical variation of both boundaries of this zone indicates that the zone is reasonably significant statistically. Hence, between December and March this area should be reasonably safe for

surface travel with the hazard increasing after that time. Structures located in this area should be relatively free from the effects of ice motion from December through March and only flaw lead activity after that time. Oil leaked under the ice in this zone would spread due to the absence of major ridges and be incorporated into flaw leads after March.

35, 36. These two zones are areas of moderate ridging intruding into Zones 30 and 34 and are basically the same. The formation of Zones 35 and 36 decrease the utility of these areas as avenues for surface travel. The mechanism for the creation of this zone is somewhat different from the mechanism responsible for other near shore areas of ridging: while most other ridges in the near shore area are shear ridges, the ridges in this area are better classified as pressure ridges which are due to ice moving down the Chukchi coast and being driven into the near shore ice.

37. This is an area of severe ridging located in the vicinity of shoals off Cape Lisburne. This zone is inshore from the average edge of mid-winter contiguous ice but within the range of boundary variation of this zone. Hence, this area should be considered to be the location of early winter ridging with moderate stability from mid-winter to early spring. After that date the edge of contiguous ice generally moves shoreward.

This area could possibly be safe for surface travel from mid-winter to early spring. However, the safety resulting from the relative stability of this ice is negated somewhat by the presence of many ridges which makes rapid surface travel very difficult.

Structures placed in this area would be subject to a great deal of ice piling and bottom plowing events. Oil spilled under the ice in this area would be incorporated into the piled ice and later into the pack ice or introduced into the pack ice via flaw lead activity.

38. This is a zone of moderate ridging located in pack ice and is included in this analysis for completeness.

39. This is a zone of moderate ridging located offshore from the mid-winter edge of contiguous ice and within the boundary of a recurring polynya. The ice within this zone is quite unstable. Surface travel would be very hazardous at anytime. Structures would be constantly subject to moving ice and piling events. Bottom plowing by ice keels should be frequent. Oil spilled under the ice in this zone would rapidly be incorporated into the pack ice.

40. This small zone just off Cape Lisburne is subject to both ridging and polynya formation. It should be considered extremely hazardous for surface operations and structures. Petroleum spilled under this zone would soon be incorporated into new ice, subject to transport with pack ice.

41, 42. These are zones of nearly constant production of new ice. This area along with Zones 39 and 40 is documented more completely in Appendix A. The ice within this zone is almost constantly moving seaward, leaving a polynya adjacent to Cape Lisburne over which new ice continuously forms. The average edge of mid-winter

ice runs across this area dividing it into two zones as a result of the very rapid formation of new ice during that period. The shoreward variation of the mid-winter ice runs very close to the shore as do the early and late spring average contiguous ice edges.

This area is particularly unsafe for surface travel at all times. However, there is the interesting possibility that structures placed here might be subject to at least a minimum of ice hazards. Oil spilled here would quickly be incorporated into newly-forming ice and be transported seaward into the pack ice.

43. This zone of moderately stable ice is located just north of Point Hope, over relatively shallow water and within a reasonably stable portion of the late spring edge of contiguous ice. This area should be safe from ridging events and significant bottom plowing. Oil spilled under this zone could be expected to spread a relatively great distance and then remain at that location between December and May.

44. A zone of intermediately safe ice located between the early spring and late spring edges of contiguous ice. Because of the variation of the boundaries, this zone illustrates the transition between the relatively stable Zone 43 and the unstable Zone 45 described next.

45. This is a small zone located within the average edge of mid-winter contiguous ice and adjacent to the recurring polynya (41 and 42). Generally, this zone exists in this vicinity but its precise

location changes frequently. This is an area where newly formed ice from the adjacent polynya is compacted from time to time and at other times is broken away. It is generally unsafe for surface travel. Structures placed within this zone would be subject to minor piling events but probably very little bottom plowing. Oil leaked under this zone during December through May will very likely become incorporated into compacted new ice and subsequently enter the pack ice region.

46. In this zone the edge of contiguous ice remains constant throughout the ice season. An apron of ice generally extends seaward from the shore. Pack ice rounding Pt. Hope occasionally results in flaw lead activity at the west end of this zone. Statistically the zone varies significantly with the seaward edge migrating occasionally very close to shore. This zone should be moderately safe for surface travel as long as quick access to the shore is maintained. Structures placed in this zone would be subject to a minimum of ridging activity. An oil leak occuring under this area between December and May would spread along the underside of this relatively smooth ice and remain until breakup in late spring or until a flaw lead developed allowing the oil-contaminated ice to drift into the pack ice region.

47. This zone is the location of a recurring polynya formed by the ice within this zone and Zone 46 breaking away and drifting southward (into Zone 48). This area is completely unsafe for surface travel during the ice season. However, a bottom-founded structure would probably encounter a minimum of destructive ice

conditions. Oil spilled under this zone would soon be incorporated into newly formed ice and subsequently into the pack ice.

48. This zone, lying in outer Kotzebue Sound, is an area of ice compaction and growth. New ice created in Zone 47 is driven into this area through the ice season. Considerable compaction of the ice is evident on successive Landsat images. The ice in this area is growing in thickness due to both compaction and freezing of new ice.

Surface travel in this area would be extremely hazardous throughout the ice season. Structures placed here would be subject to nearly constant ice piling although bottom plowing may not represent a severe hazard. Oil spilled in this area during the ice season would become incorporated into the thickening and compacting ice and would be slowly transported southward toward Zone 54.

49. This zone of ice is similar to Zone 48 except that it is located between the mid-winter and late spring edges of ice and is stationary for several weeks at a time during this period. The ice within this zone could be used for surface operations during the period December through April providing that provisions for the rapid evacuation of personnel are maintained. Structures placed within this zone would be subject to some ridging and piling of ice at all times. Ocean floor plowing should not represent a major hazard. Oil spilled under the ice in this zone would become trapped beneath the ice and be transported with the ice during breakup events. The oil could also be subject to lead pumping. The actual

length of ice trajectories during these events is relatively small with the result that spills of this nature would probably be retained in the vicinity for the balance of the ice season.

50. This zone of ice is shoreward of the late spring ice edge. Examination of Landsat imagery of this area reveals linear features which are very likely shear ridges running close to and parallel with the shore. Because of the existence of these shear ridges this zone was separated from Zone 46. These ridges are most likely formed during November and December and remain with the ice in this zone until May. During this period surface travel within this zone is relatively safe. Structures placed here may be subject to some ridge-building activity in November and December and some bottom plowing might occur during these events. Oil spilled under the ice could be expected to spread somewhat as a result of the relatively smooth undersurface of the ice in most of this zone. It would then remain in place until April-May.

51. This large zone of relatively stable ice is located inshore of the late spring ice edge including inner Kotzebue Sound. During the period of formation in November-December, dynamic ice events may take place in this zone; pressure and shear ridges may form - particularly in Kotzebue Sound - creating conditions hazardous to structures. Following that period and until April, this surface should be fairly safe for surface travel. Oil spilled here during November-December would most likely be incorporated into the ice

somewhere within the zone - depending on the nature of the dynamic ice events during that period. After that time oil would spread out on the relatively smooth undersurface of the ice and remain until breakup around May.

52. This zone of ice within Kotzebue Sound is located between the early and late spring edges of fast ice. Analysis of contiguous ice edge variations shows that sometime between early and late spring the ice within this zone is broken up. From December until the ice breaks up this area should be safe for surface travel. Structures placed within this zone would be subject to ridging activity during November-December but generally not after that date. Oil spilled under the ice will remain until springtime breakup events and would only be slowly transported away after that time.

53. This is a zone of moderate ridging located between the mid-winter and early spring average edge of contiguous ice and the late spring average edge of contiguous ice. The ridges in this area could be created at almost any time because of the high statistical variation of this zone. This area is dangerous for surface travel at all times. Structures could be subject to ice piling events and bottom plowing at almost any time. Oil spilled under the ice would soon become incorporated into broken ice within a few weeks of a spill.

54. This is an area of moderate ridging located outside the average mid-winter edge of contiguous ice in outer Kotzebue Sound. The ridges created in this area are largely shear ridges and arise as a result of motion of ice toward Bering Strait. This behavior is largely a continuation of the process originated in Zones 47 and 48.

This area is within the extreme variation boundaries of contiguous ice for mid-winter and early spring and could be considered for surface travel between December and March or April. However, this ice is highly prone to breaking up at all times and therefore surface operations should include contingency plans for rapid retreat from this zone. Structures placed within this zone would be subject to ice piling events at any time. Bottom plowing is also a definite possibility in areas less than 20 meters deep during November through April. Oil leaked under this zone would be trapped in pools between ridge keels and other keels related to the generally rough surface of this zone. However, there is a high probability of ice breakage and subsequent motion of ice allowing lead pumping of oil.

55. This is an area of moderate ridging located beyond the average edge of mid-winter contiguous ice. Shear type ridges are created in this zone largely by ice being pushed out Bering Strait and being compressed against contiguous ice in that process. This area is occasionally within the contiguous ice zone but has a high pro-

bability of being sheared or broken free. It is generally a very dangerous area for surface travel. Structures placed within this zone would be subject to almost constant ridging processes and, in locations less than 20 meters in depth, bottom plowing would take place. Oil spilled under the ice in this zone would generally become trapped. However, since the ice in this zone is frequently broken free, such trapped oil would soon be introduced into the pack ice.

56. This area of severe ridging is located offshore from the average edge of mid-winter contiguous ice. This zone is similar to Zone 55 except that the density of ridging and the relative stability is increased, (see description of Zone 55) but not sufficiently to cause this zone to be considered safe for surface operations.

57, 58. These are zones of moderate and severe ridging respectively, located inshore from the average edge of early spring contiguous ice and offshore from the average edge of mid-winter contiguous ice. This situation is reverse from the spatial relationship of these two average edges elsewhere along the coast. Further the statistical variation of the early spring contiguous ice edge is less than the variation of the mid-winter ice edge. These data support the concept of a building-up of stable ice in this area during the winter and early spring parts of the ice season while elsewhere along the coast, maximum build-up generally occurs by mid-winter. Presumably this effect is a result of the nearly constant motion of ice out of Bering Strait creating many parallel s-type ridges along this area of the coast.

This area should be considered for surface travel only in early spring. However, the surface roughness at that time would be a impede evacuation attempts from dangerous ice conditions. Structures placed in these zones would be subject to pressured ice events during nearly all the ice season. Bottom plowing is also a distinct possibility at nearly all times. Oil spilled under this zone has a high probability of entrapment in pressured ice.

59. This is an area of severe ridging located inshore from the average edges of contiguous ice for mid-winter, early spring and late spring. Hence, this zone is constructed early (Nov.-Dec.) in the ice year and remains until late spring or early summer. It is very likely that this ice is securely grounded on the relatively shallow ($\sim$ 8m) shoals mapped in this area.

Because of its stability, the ice in this zone could be used for surface operations many months of the year. However, the surface roughness should create considerable logistical problems. Structures placed in this zone would usually be subject to ice piling and bottom plowing events early (Nov.-Dec.) in the ice year. Oil spilled under this zone would be incorporated into piled ice between November and December and entrapped under piled ice after that time. Later, during May, such oil would be released into the open water with the break-up of the ice in this zone.

60. This zone contains a rapid transition of ice conditions within two very short distances between shore and the average edge of contiguous ice. It is interesting to note that not only do the average edges of contiguous ice coincide for each season, but the variations on the seaward of this line are very small indicating a nearly constant ice condition for this zone from December through late May. Further, although linear features parallel to the coast can be identified on many images, it is difficult to establish whether these features represent ridge systems or boundaries between ice types.

Based on the available information and the morphological behavior pattern of ice moving through Bering Strait, it should be expected that the ice in this zone is formed early in the ice year (December) and might remain until May. Because of the nearly constant motion of ice out Bering Strait, s-type ridges are constructed along the seaward boundary of this zone. However, the variation of the edge of this zone on the landward side of the average position is large, indicating that ridges may be constructed and carried away in an alternating sequence along this portion of the coast. Further, it is likely that the ice adjacent to the shore is rough because of this same process being operative during its formation.

This zone is therefore not entirely safe for surface travel - the relative danger increasing significantly with distance beyond well grounded ridges. Similarly the ice conditions imposed on structures would vary considerably across this zone. Finally, oil

spilled under the ice in this zone would be subject to pooling as a result of the rough undersurface and introduction into the pack ice during the occasional break-off events.

61. This is a zone of relatively smooth, stable ice formed early in the ice year and remaining in place until late spring. It should generally be moderately safe for surface travel from December through May. Structures placed in this zone should be relatively free from ice piling events and bottom plowing. Oil spilled under this zone would be subject to considerable spreading because of the relatively smooth undersurface.

62. This is a zone of moderate ridging and variable stability throughout the ice season. It is generally unsafe for surface travel over long periods of time although brief excursions could be safely carried out providing ice conditions were monitored carefully. Structures in this zone would generally be subject to ice piling conditions at any time. Oil spilled under this zone would tend to become trapped under the relatively rough undersurface and be introduced into the pack ice during the occasional ice breaking events.

63. This is a broad zone of unstable ice located over relatively shallow waters running from Cape Espenberg to Wales. This zone has some unusual characteristics: the variation of the edges of contiguous ice run adjacent to the shore. Hence the area can be relatively broad at one time and break-up to the shore at other times. This area should be considered unsafe for surface travel. Structures placed within this zone would probably not be exempt from ice piling events for very long periods of time. Oil spilled

under this zone would soon become incorporated into broken and refreezing pack ice.

V. Discussion

A. A Discussion of the Models Developed to Describe the Extent and Behavior of Near Shore Ice, Its Limitations and Capabilities.

1. Limitations

The models developed here for Chukchi and Beaufort Sea ice morphology are based on statistical analysis of five years' ice data. The models represent an average of conditions observed during only those years. An obvious limitation, then, is the lack of really long-term data and the possibility that the ice during the years observed does not represent long-term average conditons.

In addition, even if by some chance the models do represent the long term average conditions, there is little hint of what variability in conditions should be expected over a span of twenty to thirty years. Hence, it is not certain what range of ice conditions to anticipate during the active life of an offshore oil field.

For instance, during this period of observation the melt season weather conditions have been reasonably mild. Near shore ice has broken up and melted in place. Grounded ridge systems have slowly broken contact with the sea floor and drifted away. We have not had the opportunity to access the potential hazard created if a major storm were to occur during this period when great quantities of highly mobile ice are present in the near shore areas.

Finally, the model developed here is only semi-dynamic in that only a few <u>processes</u> involved in near shore ice morphology have been identified. To develop a dynamic morphology a much more extensive analysis would be necessary.

2. Capabilities

Despite the limitations indicated above, the models developed represent the state of knowledge of comprehensive regional ice morphology in the Chukchi and Beaufort Seas available in the public domain. Certainly the various zones delineated to describe near shore ice morphology should be considered an initial stage of any assessment of hazards related to activities of the offshore development along these coasts.

The chief capabilities include:

1. an assessment of the relative safety of personnel and equipment operating on offshore ice in the various zones identified.
2. a preliminary assessment of the mid-winter to late spring probability of major ice displacement occurring in the zones identified.
3. a preliminary assessment of the probability of a structure placed in each given zone having to withstand the bearing load of a major ridge system.
4. a preliminary assessment of the probability of subsurface structures being disturbed by bottom plowing by major ridge systems.
5. a zone-by-zone assessment of the fate of a possible under ice petroleum spill.

B. A Discussion of How the Results of This Investigation Have Been or May be Applied to Nearshore and Shoreline Construction.

These results are quasi-regional in nature and not site-specific. For that reason they should be used when considering regional construction requirements. For instance, once a construction technique has been established for structures placed in a particular set of ice conditions, the area of applicability of that technique has been established. This could be of value in terms of overall economic estimates.

For instance, it a particular type of technique for constructing drilling platforms was found acceptable for the ice conditions found in one of the zones mapped for the Beaufort Sea, the range of applicability could be established by the boundaries of the zone. Further, when comparing the total cost incurred by two or more techniques, each corresponding to different ice zones located over the same field, the total number of wells and their configuration might be in part determined by the configuration of the ice zones.

C. A Discussion of the Detectabilityof Ice Islands by Landsat.

At the outset of this analysis it was anticipated that ice islands in the pack ice during winter and spring would be detectable because their deep draft would make them susceptible to oceanic currents and to a certain extent drive them through the pack leaving a wake behind. Only on one occasion was anything like this observed and it was not possible to verify the ice island possibility. (Actually, the image was acquired before the initiation of this project.)

As stated earlier in this report, on two occasions, small ice islands were observed apparently grounded in the contiguous ice zone. Both times an attempt was made to locate the islands on Landsat imagery. Neither time could they be found. In both cases, the islands had broken into several fragments.

We now think that the best assessment of the number of ice islands could be made by using summertime imagery of the polar pack. The analysis would consist of looking for large pieces of ice with perhaps a small polynya to one side. Week-by-week observation should show a slightly different trajectory for an ice island over ordinary pack ice.

VI. Recommendations

Landsat data has been shown to be a useful tool for construction of sea ice morphology. However, its greatest utility would be realized if the data could be used for the following activities:

1. Navigations and emergency warning for field crews operating on the ice.
2. Monitoring ice conditions in the event of an oil spill, in order to predict the immediate fate of the spill.
3. Monitoring ice conditions which may alter the ice loading force on offshore structures.
4. Monitoring ice conditions which may influence migratory patterns or feeding places of sea-related wildlife (whales, seals, acquatic birds, etc.)
5. Monitoring ice conditons in order to help navigate ship traffic.

At present Landsat is useless for these activities because of the long time delay between time of data acquistion and its availability to users. To correct this situation, this project recommends the establishment of a "quick-look" capability at Gilmore Creek, Alaska, where NASA already has a Landsat data receiving station. For ice purposes, only band 7 need be recorded but it would be necessary to obtain the imagery at highest resolution.

VII. Other Applications of Results

The results reported here were derived in order to assess hazards related to petrochemical extraction activities in the Alaskan near-shore areas. The data have also been of interest to biologists analyzing the migratory patterns of whales, the feeding locations of walruses and seals and flight patterns of migratory arctic birds.

VIII. Interest by Agencies and Companies

Interim copies of these results have been given to State and Federal agencies and representatives of various petroleum companies performing exploratory work in Alaska. However, because of the nature of statistical work, no final results have been available before compilation of this final report. We anticipate making these results available to potentially interested companies and agencies in the near future.

IX. Future Activities

The statistical results reported here serve as a comprehensive regional background for understanding Beaufort and Chukchi seas' nearshore ice morphology. In the process of developing these results, several ice related phenomena and processes have been identified which appear to be worthy of further investigation. Funding for these activiites will be sought from the appropriate agency or companies.

X. Publications

Because of the statistical nature of this work, no publications have been possible until the compilation of the results reported here.

XI. List of References

No direct references to other publications are made in this report. This is largely because of the original nature of this statistical analysis. However, use was made of the following publications:

Ahlnas, K., and G. Wendler, Arctic sea-ice conditions in early spring viewed by satellite, Arctic and Alpine Research, Vol. 9, No. 1, p. 61-72, 1977.

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Kovacs, A., and M. Mellor, Sea ice morphology and ice as a geologic agent in the southern Beaufort Sea, Proceedings of the Symposium on Beaufort Sea Coast and Shelf Research, Arctic Institute of North America, 1974.

Kovacs, Austin, and Anthony J. Gow, Some characteristics of grounded floebergs near Prudhoe Bay, Alaska, CRREL Report 76-34, prepared for NOAA, Sept. 1976.

Kovacs, Austin, Grounded ice in the fast ice zone along the Beaufort Sea coast of Alaska, ERREL report 76-32, prepared for NOAA, Sept. 1976.

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Kovacs, Austin, Sea ice thickness profiling and under ice oil entrapment, 9th Annual Offshore Technology Conference, Houston, Texas, May 1977.

Nelson, Richard K., Hunters of the northern ice, University of Chicago Press, 1969.

Reimnitz, E., and P. W. Barnes, Studies of the inner shelf and coastal sedimentation environment of the Beaufort Sea from ERTS-1, NASA Report No. NASA-CR-132240, p. 3, 1973.

Reimnitz, Erk, Larry Toimil, and Peter Barnes, Development of the Stamukhi zone and its relationship to arctic shelf processes and morphology, Beaufort Sea, Alaska, U. S. Geological Survey, Menlo Park, California, 1976.

Searby, Harold W., and Marcelle Hunter, Climate of the north slope Alaska, U. S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, February 1971.

Seifert, Richard D., The structure of shorefast ice off the north slope of Alaska, M. S. Theses, University of Alaska, May 1973.

Shapiro, Lewis H. and John J. Burns, Satellite observations of sea ice movement in the Bering Strait region, preprint, 1975.

Stringer, W. J., Shore-fast ice in vicinity of Harrison Bay, Northern Engineer, 5, No. 4, 1974.

Stringer, W. J., The morphology of Beaufort Sea shore-fast ice, Proceedings of the Arctic Institute of North America, December 1974.

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APPENDIX A

ON THE FEASIBILITY OF A SHIP LOADING FACILITY AT CAPE DYER OR CAPE THOMPSON, ALASKA

There are no ports along Alaska's northwest coast. Further, that coast is the site of rather severe ice conditions. There is a good possibility that in the near future resource exploitation in the northwest region will require year-round ship loading facilities.

In the absence of a suitable port, nearshore loading facilities for commodities such as coal and oil might be built in locations where deep waters are located sufficiently close to shore for such structures to be economically feasible. However, because of the severe ice conditions along this coast, it would seem that even this sort of loading facility would be out of the question.

Generally speaking, wind-driven ice builds massive shear ridges along coastal headlands parallel to ice motion. Many of these ridges are grounded in water 60-feet deep and extend over 20-feet above sea level. Maintenance of an offshore loading facility in the presence of these conditions would be difficult if not impossible. The most likely locations for offshore loading facilities are locations where deep water is found close to shore and severe ice conditions are at a minimum.

As part of an extensive nearshore ice survey two likely locations for such facilities have been located. Both of these locations are found at the extreme western end of the Brooks Range. They are: Cape Dyer, located between Cape Lisburne and Point Hope, and Cape Thompson, located southeast of Point Hope.

Cape Dyer is on a north-south oriented portion of coast open to the sea to the west and northwest. Cape Lisburne offers protection to the north while the large spit at Point Hope gives protection from the south and southwest. Steep cliffs at Cape Dyer apparently extend to a depth of 14-16 meters offering the possibility that ships could be loaded directly from boom-like structures extending from shore.

Examination of Chukchi Sea satellite images from 1973 to the present (1977) indicates that the normal ice motion in the vicinity of Cape Dyer is west of south following the tangent between Cape Lisburne and Point Hope. Water depths are too great along this tangent for grounding of any shear ridges to take place. Close examination of satellite images of Cape Dyer on seventy occasions shows that ice does form in this indentation but it is often carried out to sea with the ice pack, driven by east and northeast winds which push the ice pack out Bering Strait. Hence, even the shore-bound annual ice does not attain the six-foot thickness usually attributed to full-season annual ice.

Although shearing motion cannot take place along Cape Dyer, ice can be driven into the shore from the west and northwest. Fortunately, the extreme wind speeds from these directions occur less frequently than from other directions, and the sum of wind frequency from the west and northwest is only ten percent. Corresponding to this, one occasion was observed on satellite imagery when large pans of ice were driven into the shore at Cape Dyer. This episode certainly would have made ship loading operations difficult during the event. However, direct observations as well as wind records indicate that this is a rare occurrence.

Cape Thompson is located to the south, on the opposite side of Point Hope, on a northwest to southeast tending portion of the coast. It is even better protected from normal shearing events than Cape Dyer, but is open to ice motion from the west to southeast. Further, although Cape Thompson also consists of cliffs extending beneath the ocean, available charts indicate water depth there of less than 13 meters. While ten percent of the winds at Cape Dyer could cause adverse ice conditions, at Cape Thompson twenty-two percent of the winds are in this category. Beyond that, the greatest winds observed in that area - 70 mph - have been from the southeast and could possibly cause shearing along the coast at Cape Thompson. During the four years of satellite observation, no such event was witnessed. However, although a large polynya exists just to the south of Cape Thompson (created by southward motion of the Chukchi ice) there is always a small shelf of ice at least a kilometer wide extending seaward from Cape Thompson. The nature of this ice is not obvious (first year smooth ice, shear ridges, etc.) from satellite imagery. It is quite possible that because of this near shore ice and the shallow water that a ship loading facility at Cape Thompson would necessarily include a bottom-founded offshore structure.

Thus, of the two locations, it would appear that Cape Dyer is the better location for a shore line ship loading facility. However, during wind conditions that create the greatest hazards for approach to Cape Dyer, the polynya at Cape Thompson is enhanced - thus offering ships awaiting approach to Cape Dyer around Point Hope an ice-free place to wait.

CAPE DYER

Date	Scene I. D.	Comments
1973		
6 Mar.	1226-22160-7	Young ice - large pans offshore
7 Mar.	1227-22212-6	Not shown - large pans offshore
7 Mar.	1227-22214-6	Young ice - large pans offshore
8 Mar.	1228-22270-7	Young ice - large pans offshore
8 Mar.	1228-22273-7	Young ice
11 Mar.	1262-22160-6	Open water
12 Mar.	1263-22212-6	Still water
17 May	1298-22155-7	Even more open
19 May	1300-22265-6	Open water
19 May	1300-22271-6	Open water
4 June	1316-2253-7	Clouds
23 June	1353-22210-6	Open with occasional pans
24 June	1336-22262-7	Open
1974		
1 Mar.	1586-22104-7	First year ice frozen in place
2 Mar.	1587-22162-6	First year ice frozen in place
3 Mar.	1588-22214-7	N.S.
3 Mar.	1588-22220-7	First year ice frozen in place
4 Mar.	1589-22272-6	First year ice frozen in place
4 Mar.	1589-22275-6	First year ice frozen in place
5 Mar.	1590-22331-7	N.S.
19 Mar.	1604-22102-7	First year ice covered with dirt
20 Mar.	1605-22160-7	First year ice covered with dirt
23 Mar.	1608-22325-6	N.S.
6 Apr.	1622-22100-7	Narrow band of ice with water offshore
7 Apr.	1623-22154-7	Narrow band of ice with new ice offshore
8 Apr.	1624-22210-7	Narrow band of ice with new ice offshore
9 Apr.	1625-22264-6	Narrow band of ice with water offshore
27 Apr.	1643-22261-7	Narrow band of ice with broken ice offshore
13 May	1659-22144-6	Narrow band of ice with open water offshore
14 May	1660-22200-6	Narrow band of ice with open water offshore
17 June	1694-22080-6	Open water with pack ice offshore
18 June	1695-22134-7	Open water
7 July	1714-22182-7	Open water
1975		
24 Feb.	1946-21585-7	First year ice
25 Feb.	1947-22040-7	N.S.
25 Feb.	1947-22043-7	First year ice
26 Feb.	1948-22094-7	First year ice
26 Feb.	1948-22101-7	N.S.
27 Feb.	1949-22152-7	N.S.
27 Feb.	1949-22155-7	N.S.
14 Mar.	1964-21580-7	New ice
1 Apr.	1982-21571-7	New ice and large first year pans
2 Apr.	1983-22025-7	New ice and large first year pans

Date	Scene I. D.	Comments
1975 Cont'd		
3 Apr.	1984-22080-7	New ice and large first year pans
3 Apr.	1984-22083-7	N.S.
10 Apr.	2078-22035-7	New ice with large pans offshore
12 Apr.	2080-22145-6	Young ice
12 Apr.	2080-22151-6	N.S.
28 Apr.	2096-22034-7	Narrow belt of first year ice with open water
29 Apr.	2097-22090-7	Narrow belt of first year ice with open water
29 Apr.	2097-22093-7	N.S.
30 Apr.	2098-22144-7	Narrow belt of first year ice with open water
16 May	2114-22033-7	Narrow belt of first year ice with open water
17 May	2115-2284-7	Clouds
3 June	2132-22034-7	Open water
5 June	2134-22151-7	N.S.
25 Oct.	2276-22021-6	Open water with pans offshore
27 Oct.	2278-22131-6	Open water with pans offshore
28 Oct.	2279-22185	Open water with pans offshore
1976		
10 Feb.	2384-22005-7	Young ice
11 Feb.	2385-22061-7	Young ice and older pans
11 Feb.	2385-22063-7	Young ice and older pans
12 Feb.	2386-22115-7	Dark image
29 Feb.	2403-22054-7	Narrow shelf first year with water offshore
29 Feb.	2403-22060-7	Narrow shelf first year with water offshore
1 Mar.	2404-22112-7	Narrow shelf first year with new ice offshore
1 Mar.	2404-22115-6	Narrow shelf first year with new ice offshore
2 Mar.	2405-22170-7	Narrow shelf first year with water offshore
2 Mar.	2405-22173	Narrow shelf first year with water offshore
17 Mar.	2420-21595-7	First year pans driven into coast
18 Mar.	2421-22053-7	First year pans driven into coast
19 Mar.	2422-22105-7	Pans driven into coast consolidate and break off, narrow shelf first year with green water offshore
19 Mar.	2422-22111-7	N.S.
20 Mar.	2423-22163-6	Narrow shelf first year with green water offshore
20 Mar.	2423-22165-6	N.S.
21 Mar.	2424-22221-6	N.S.
6 Apr.	2440-22101-7	Wide shelf of ice off coast with open leads
6 Apr.	2440-22104-7	Wide shelf of ice off coast with open leads
7 Apr.	2441-22155-6	Wide shelf of ice off coast with open leads
22 Apr.	2456-21584-6	Narrow shelf of ice off coast with open leads
23 Apr.	2457-22040-6	N.S.
24 Apr.	2458-22101-7	Narrow shelf of ice off coast with open leads
15 June	2510-21572-6	Open water and occasional pans
23 July	2548-22072-6	Open water with many pans
7 June	5415-21361-6	Narrow shelf of ice with broken pack ice

CAPE DYER (Cont'd)

Date	Scene I. D.	Comments
1976 Cont'd		
22 July	2547-2202	No ice
8 Aug.	2564-21555	No ice
8 Aug.	2564-21561	No ice
9 Aug.	2565-22013	No ice
25 Aug.	2581-21500	Too far south
26 Aug.	2582-21552	No ice
13 Sept.	2600-21545	No ice
14 Sept.	2601-22003	No ice
10 Oct.	2637-21592	No ice

CAPE THOMPSON

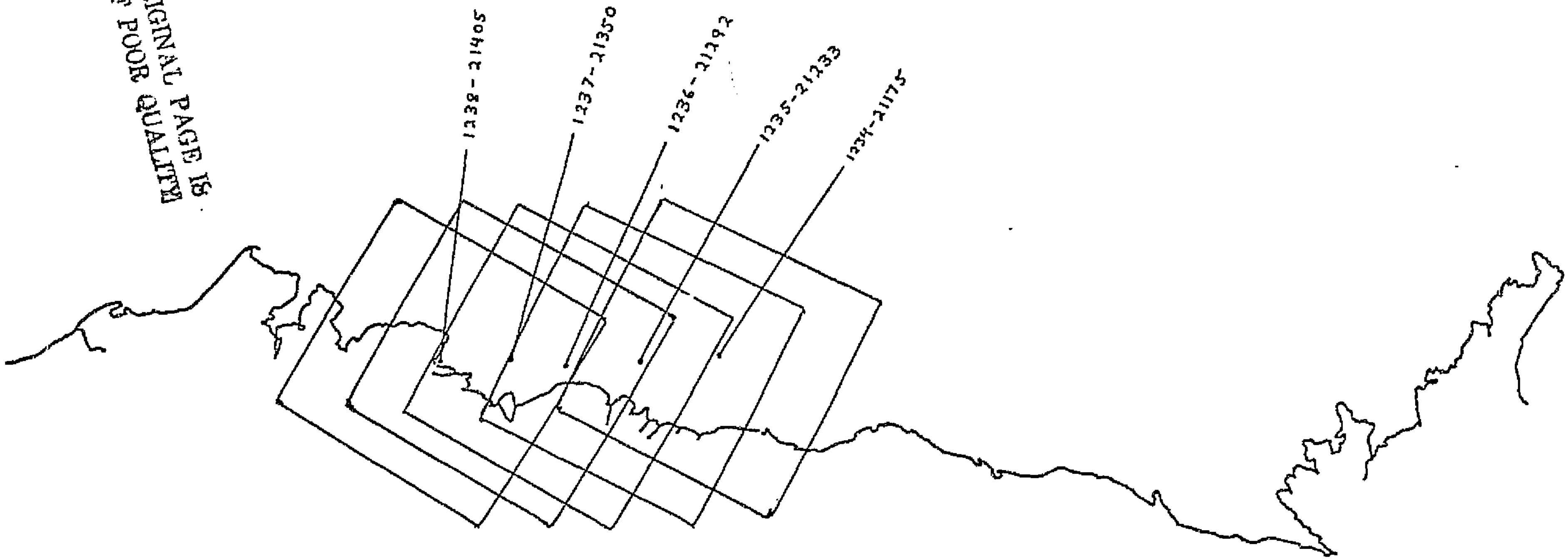
Date	Scene I. D.	Comments
1972		
1 Aug.	1009-22090	No ice
2 Aug.	1010-22145	No ice
6 Sept.	1045-22091	No ice
7 Sept.	1046-22145	No ice
1973		
6 Mar.	1226-22160	Broad band first year ice near shore new ice beyond
7 Mar.	1227-22214	Broad band first year ice near shore, new ice beyond
8 Mar.	1228-22273	Broad band first year ice near shore, new ice beyond
10 Apr.	1261-22104	Clouds
11 Apr.	1262-22160	Broad band first year ice near shore, lead beyond
17 May	1298-22155	Broad band first year ice near shore, new ice beyond
17 May	1298-22161	N.S.
2 June	1314-22041	Broad band first year ice near shore, open water beyond
2 June	1314-22043	Broad band first year ice near shore, open water beyond
4 June	1316-22153	Broad band first year ice near shore, open water beyond
22 June	1334-22155	N.S.
23 June	1335-22210	Coast clear, pack ice beyond
9 July	1351-22095	N.S.
13 Aug.	1386-22031	No ice N.S.
14 Aug.	1387-22090	No ice
14 Aug.	1387-22092	No ice
2 Sept.	1406-22142	No ice
3 Sept.	1407-22200	No ice
22 Sept.	1426-22252	No ice
7 Oct.	1441-22075	No ice
7 Oct.	1441-22081	No ice
29 Nov.	1494-22011	
1974		
9 Feb.	1566-21595	Too far south
10 Feb.	1567-22051	Broad band first year ice near shore, new ice beyond
10 Feb.	1567-22053	Too far south
1 Mar.	1586-22104	Large expanse first ice extending from shore
1 Mar.	1586-22110	N.S.
2 Mar.	1587-22162	Large expanse first year extending from shore broken by lead
18 Mar.	1603-22043	Large expanse first year extending from shore broken by lead.

CAPE THOMPSON (Cont'd)

Date	Scene I. D.	Comments
1974 Cont'd		
19 Mar.	1604-22102	Large expanse first year extending from shore broken by lead
19 Mar.	1604-22104	Too far south
20 Mar.	1605-22160	Large expanse first year extending from shore broken by lead
5 Apr.	1621-22041	Narrow shelf near shore, new ice beyond
5 Apr.	1621-22044	Too far south
6 Apr.	1622-22100	Narrow shelf near shore, new ice beyond
7 Apr.	1623-22154	Narrow shelf near shore, new ice beyond
10 May	1656-21580	Narrow shelf near shore, new ice beyond
13 May	1659-22144	Narrow shelf near shore, new ice beyond
28 May	1674-21573	Too far south
29 May	1675-22031	Too far south
30 May	1676-22090	Too far south
31 May	1677-22141	Can't find
17 June	1694-22080	
17 June	1694-22082	Too far south
18 June	1695-22134	Broad shelf decaying ice offshore
4 July	1711-22014	
4 July	1711-22020	Open water
23 July	1730-22064	No ice
3 Oct.	1802-22040	No ice
4 Oct.	1803-22094	No ice
22 Oct.	1821-22094	No ice
1975		
24 Feb.	1946-21585	Shelf of first year with new ice beyond
25 Feb.	1947-22043	Shelf of first year with new ice beyond
26 Feb.	1948-22101	Shelf of first year with new ice beyond
14 Mar.	1964-21580	Shelf of first year with young ice beyond
31 Mar.	1981-21512	Too far east
31 Mar.	1981-21515	Can't find folder
1 Apr.	1982-21571	Shelf of first year ice and young ice adjacent
2 Apr.	1983-22025	Shelf of first year ice and young ice adjacent
3 Apr.	1984-22083	Clouds
9 Apr.	2077-21580	Shelf of first year, young ice has broken away
10 Apr.	2078-22035	Shelf of first year, young ice has broken away
11 Apr.	2079-22093	Shelf of first year, young ice has broken away
12 Apr.	2080-22151	Shelf of first year, young ice forming adjacent
27 Apr.	2095-21580	No folder
28 Apr.	2096-22034	Shelf of first year, young ice forming adjacent
29 Apr.	2097-22093	Shelf of first year, young ice forming adjacent
14 May	2112-21520	Shelf of first year, young ice forming adjacent
15 May	2113-21574	Shelf of first year, young ice forming adjacent
16 May	2114-22033	Shelf of first year, young ice forming adjacent
2 June	2131-21580	Narrow shelf with floes adjacent
3 June	2132-22034	Narrow shelf with floes driven shoreward
5 June	2134-22151	Narrow shelf with floes drifting seaward

CAPE THOMPSON (Cont'd)

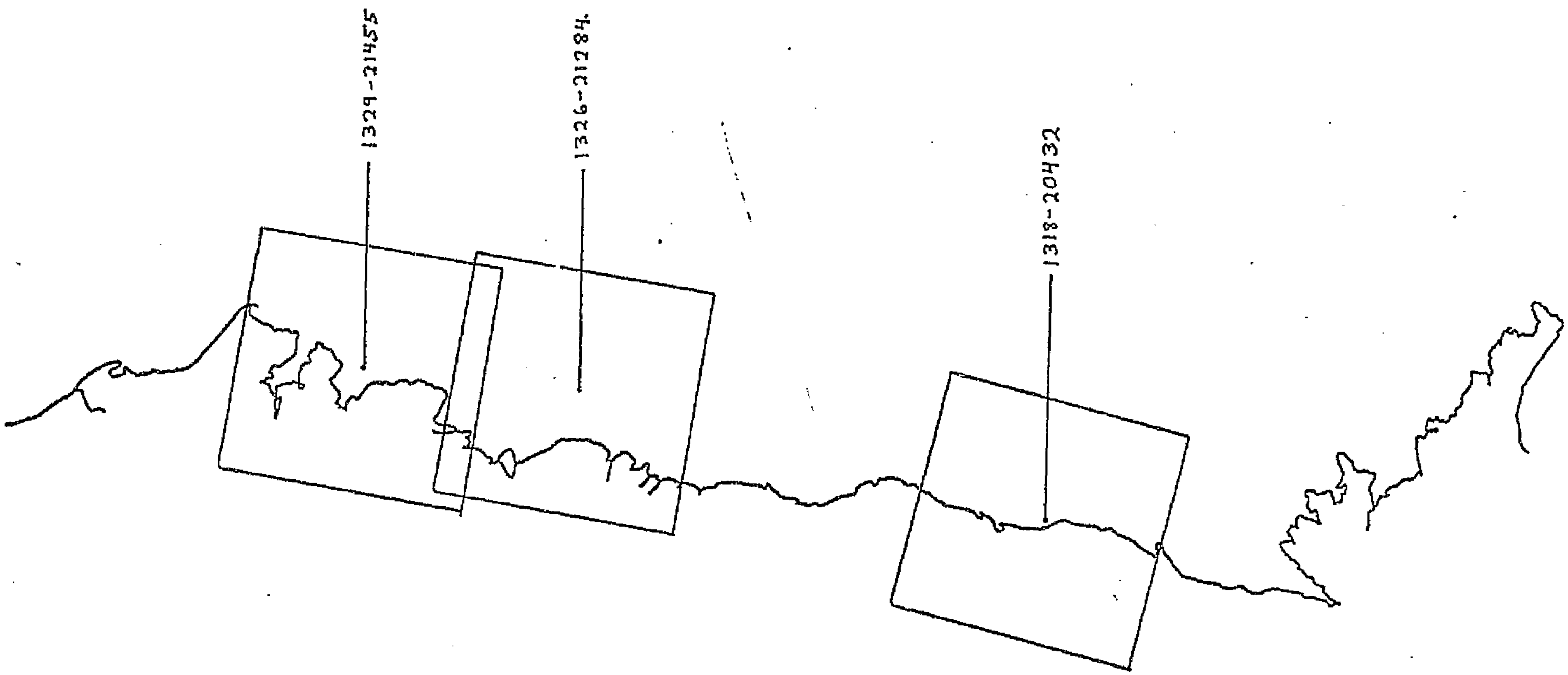
Date	Scene I. D.	Comments
1975 Cont'd		
14 Aug.	2204-22025	No ice
14 Aug.	2204-22031	Too far south
2 Sept.	2222-22023	No ice
24 Oct.	2275-21563	No ice
25 Oct.	2276-22021	
11 Nov.	2293-21561	Ice free
1976		
9 Feb.	2383-21551	Narrow shelf of ice, water beyond (narrowest part of shelf does not correspond to shallow area)
10 Feb.	2384-22005	Narrow shelf of ice, water beyond
11 Feb.	2385-22063	Narrow shelf of ice with new ice beyond
27 Feb.	2401-21544	Narrow shelf of ice with new ice beyond
29 Feb.	2403-22060	Narrow shelf of ice with new ice beyond
1 Mar.	2404-22115	Clouds
16 Mar.	2419-21541	Narrow shelf of ice with water beyond
17 Mar.	2420-21595	Narrow shelf with water beyond
18 Mar.	2421-22053	Narrow shelf with water beyond
19 Mar.	2422-22111	Narrow shelf with new to young ice beyond
2 Apr.	2436-21481	Narrow shelf with bew to young ice beyond
3 Apr.	2437-21533	Narrow shelf with contiguous thick young ice
6 Apr.	2440-22104	N.S.
20 Apr.	2454-21474	N.S.
21 Apr.	2455-21532	Coastal lead opening up
22 Apr.	2456-21584	N.S.
22 Apr.	2456-21591	
23 Apr.	2457-22042	
24 Apr.	2458-22101	Coastal lead opening again
10 May	2474-21581	Nothing in folder
14 June	2509-21514	Narrow shelf with pack ice adjacent
15 June	2510-21572	Narrow shelf with water adjacent
16 June	2511-22030	Nothing in folder
	5415-21361	Narrow shelf with pack ice adjacent



II-1 BEAUFORT SEA

MARCH 2 – MARCH 19, 1973

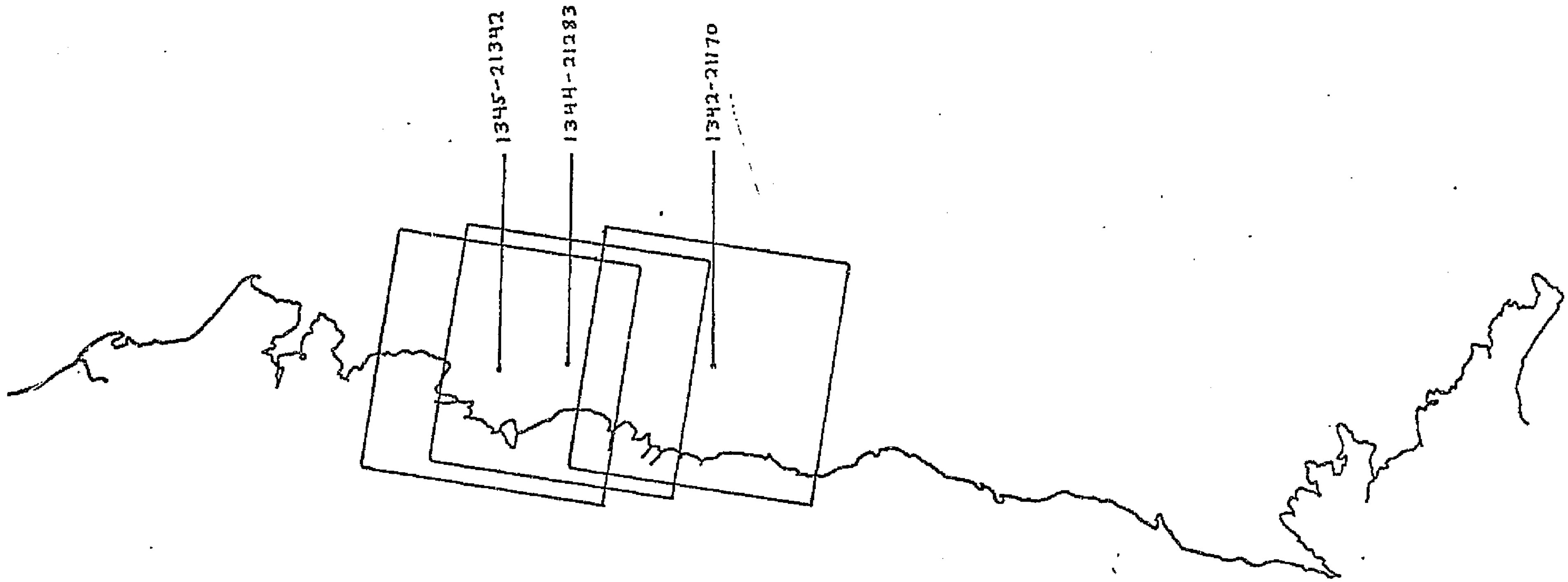
IMAGES: 1222 to 1239



II-2 BEAUFORT SEA

31 MAY - 17 JUNE 1973

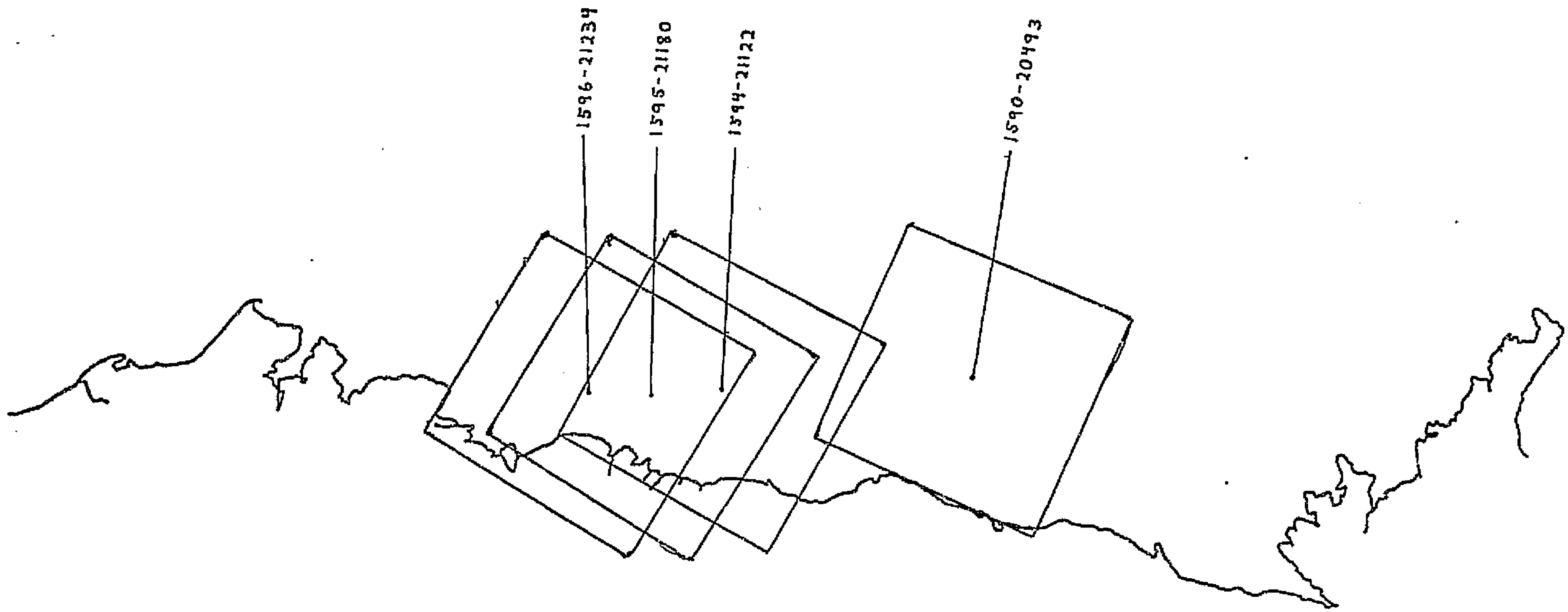
Images: 1312 - 1329



II-3 BEAUFORT SEA

18 JUNE-5 JULY 1973

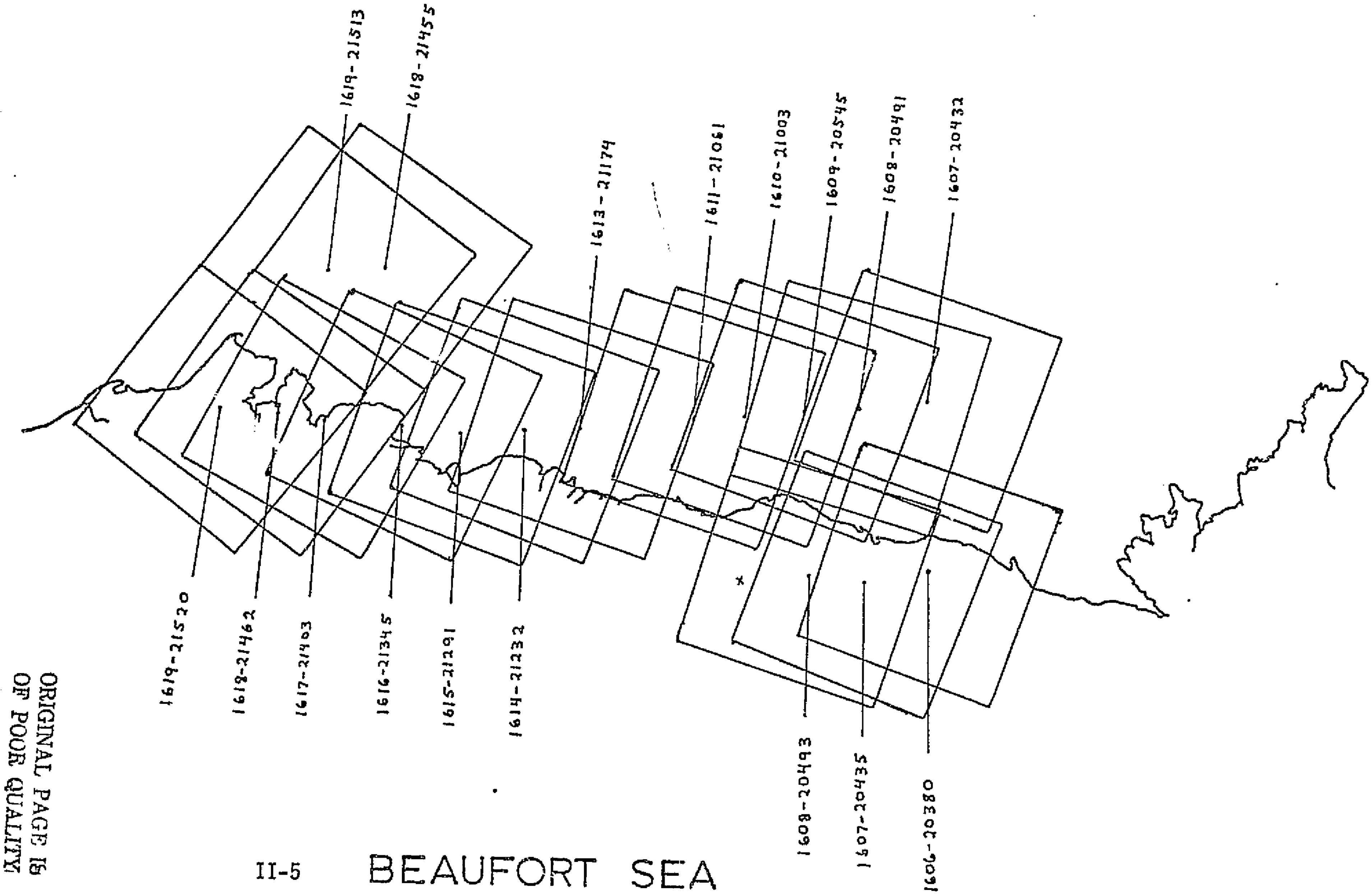
1330-1347



II-4 BEAUFORT SEA

FEBRUARY 25 - MARCH 14, 1974

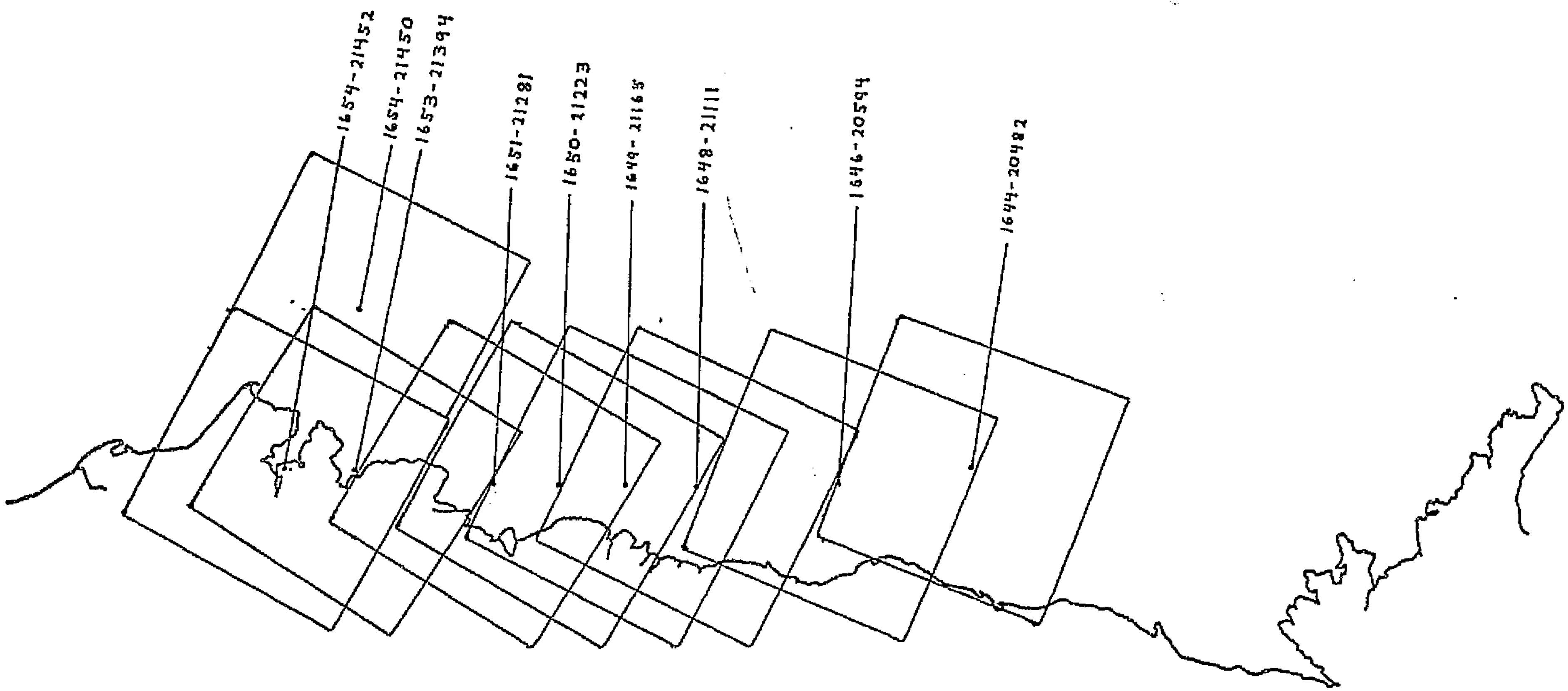
IMAGES: 1582 to 1599



II-5 BEAUFORT SEA

MARCH 15 - APRIL 3, 1974
IMAGES: 1600 to 1619

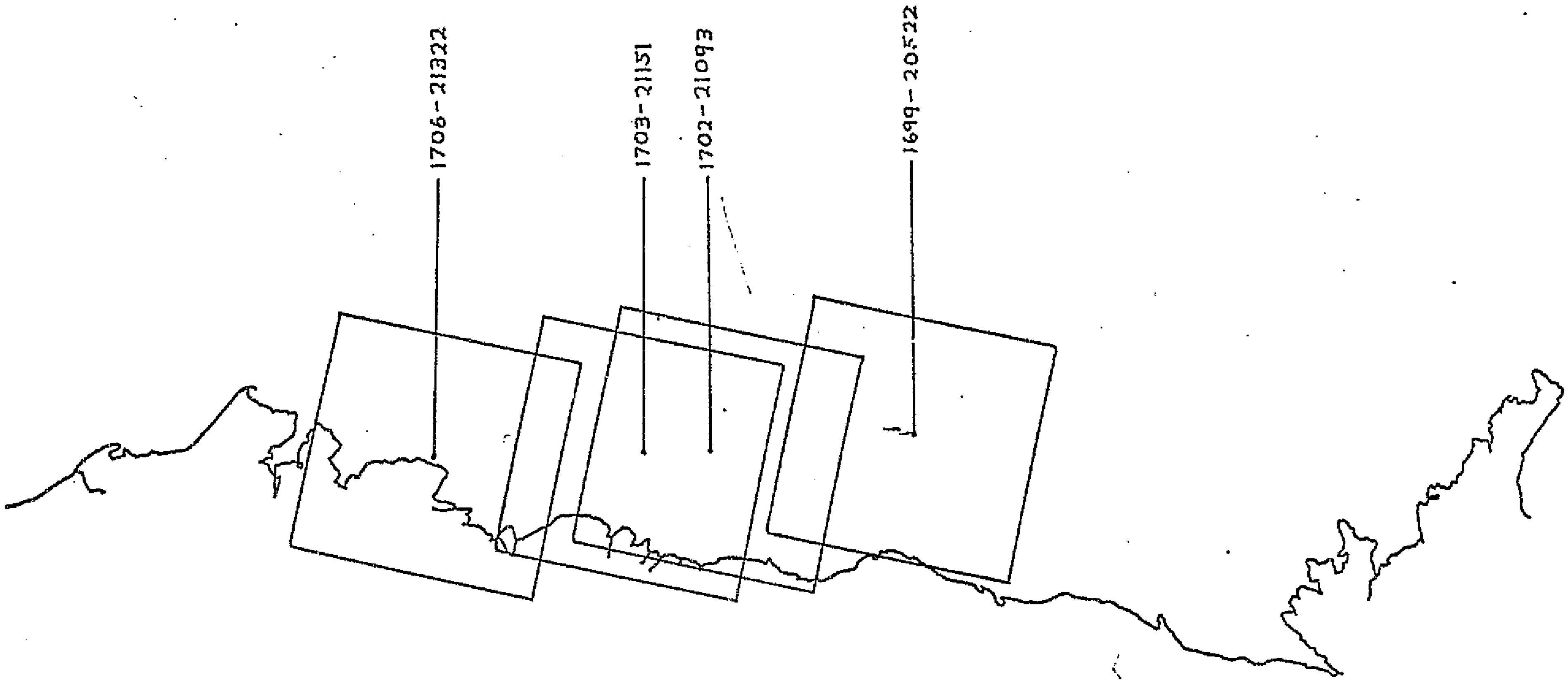
ORIGINAL PAGE IS
OF POOR QUALITY



II-6 BEAUFORT SEA

APRIL 20 - MAY 8, 1974

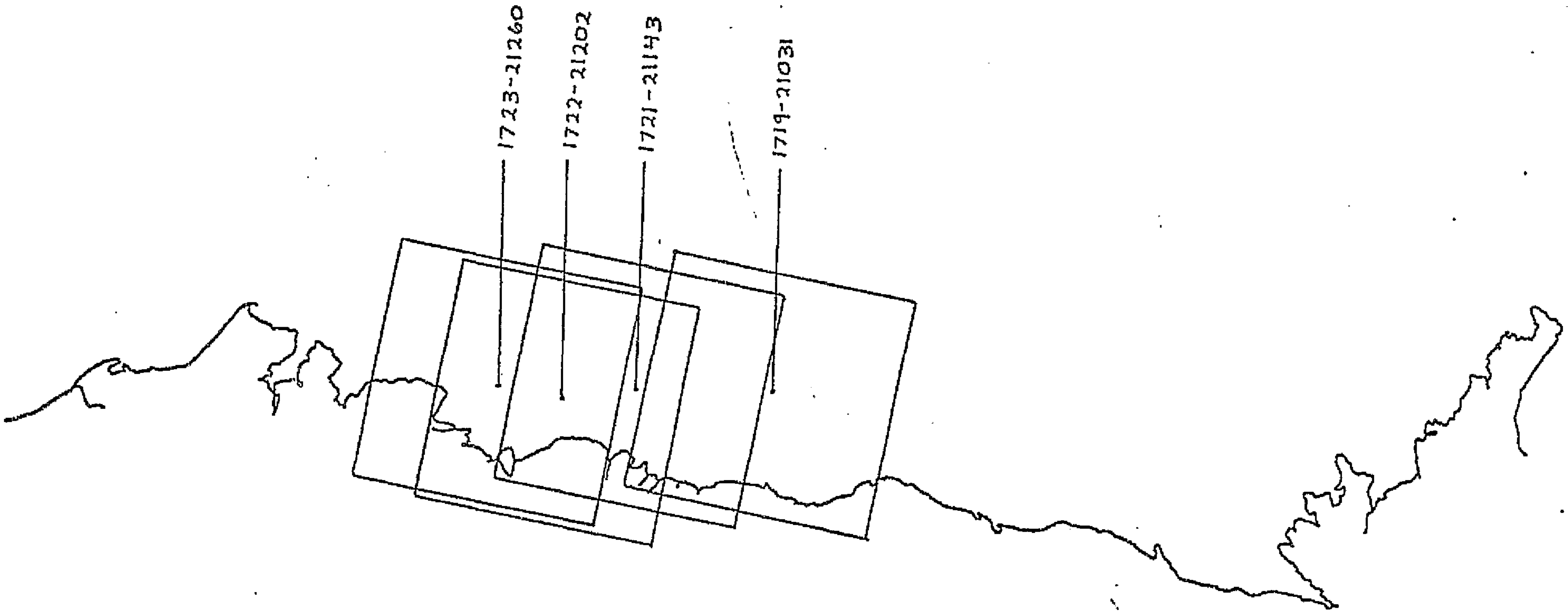
IMAGES: 1636 to 1654



II-7 BEAUFORT SEA

13 JUNE - 30 JUNE 1974

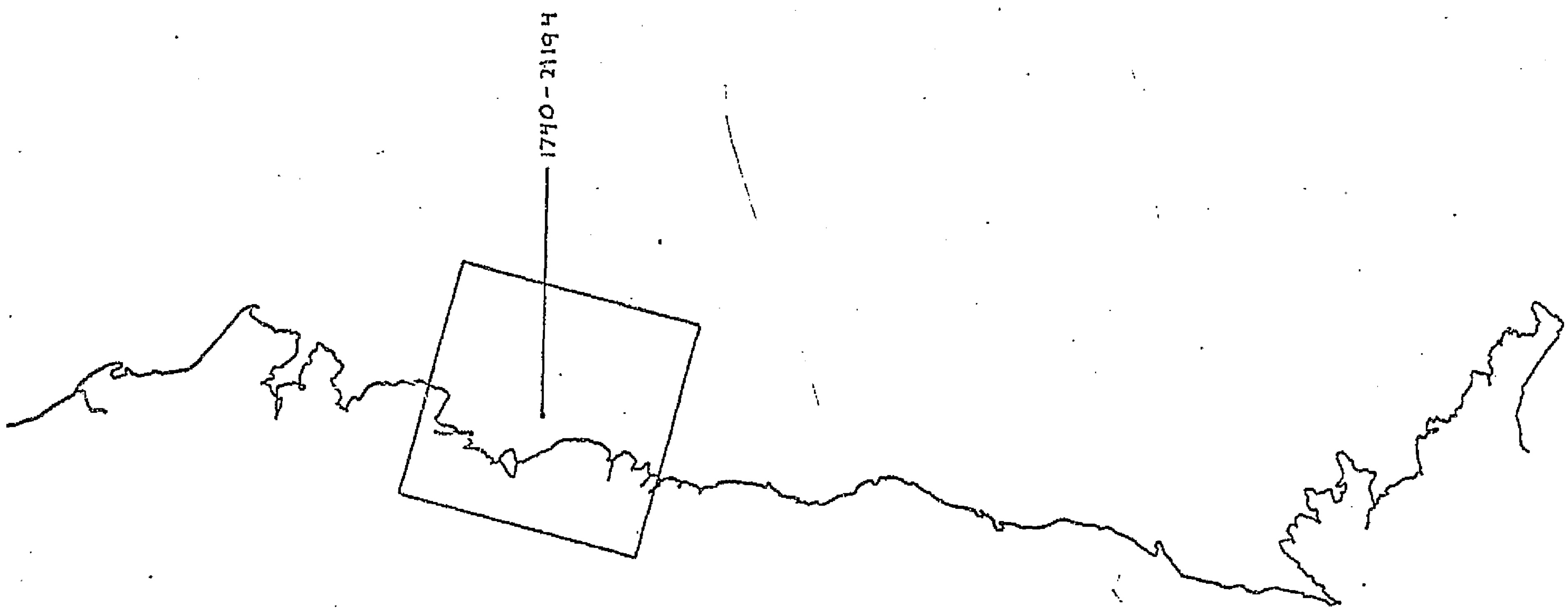
Images: 1690-1707



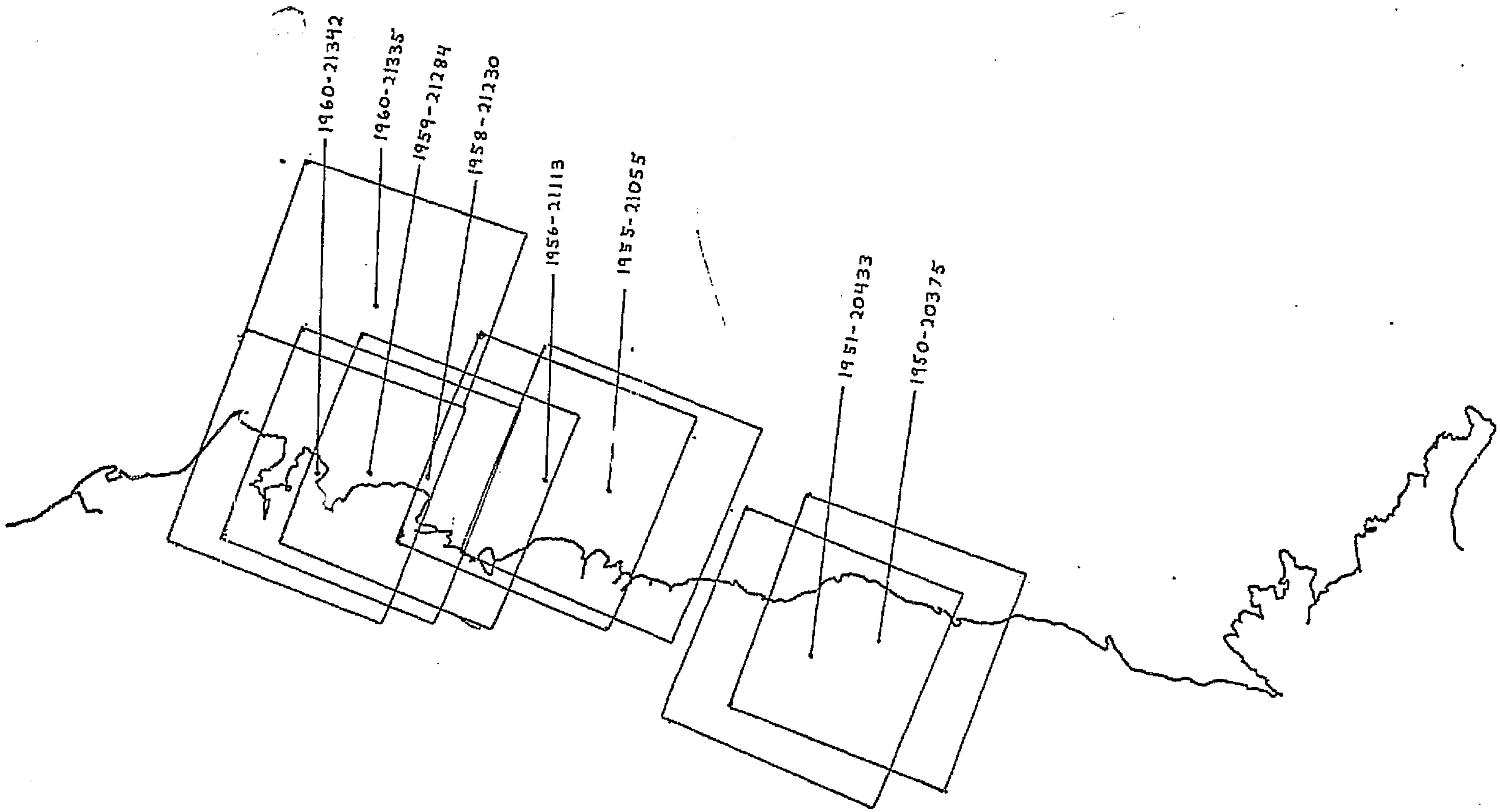
II-8 BEAUFORT SEA

1 JULY - 18 JULY 1974

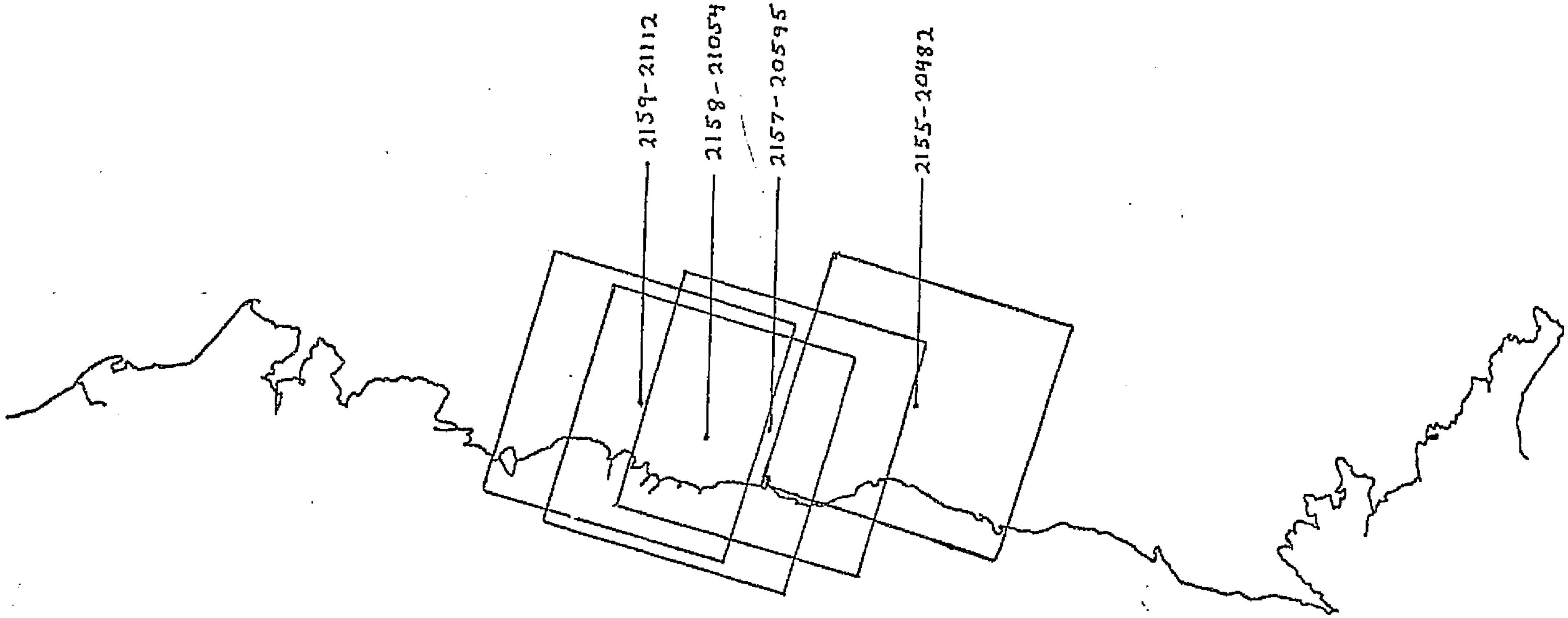
1708 - 1725



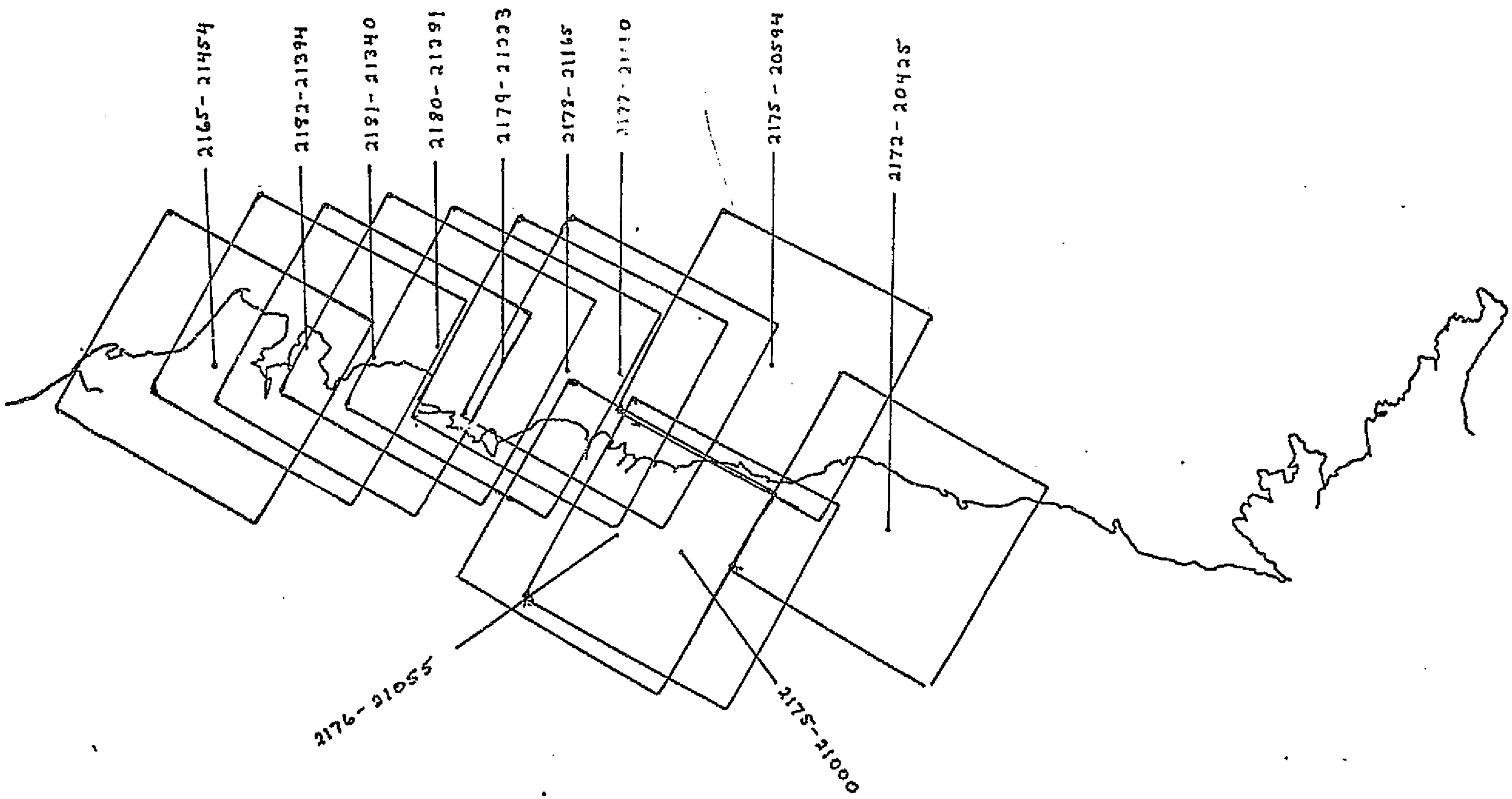
II-9 BEAUFORT SEA
19 JULY-5 AUGUST 1974
Images: 1726-1743



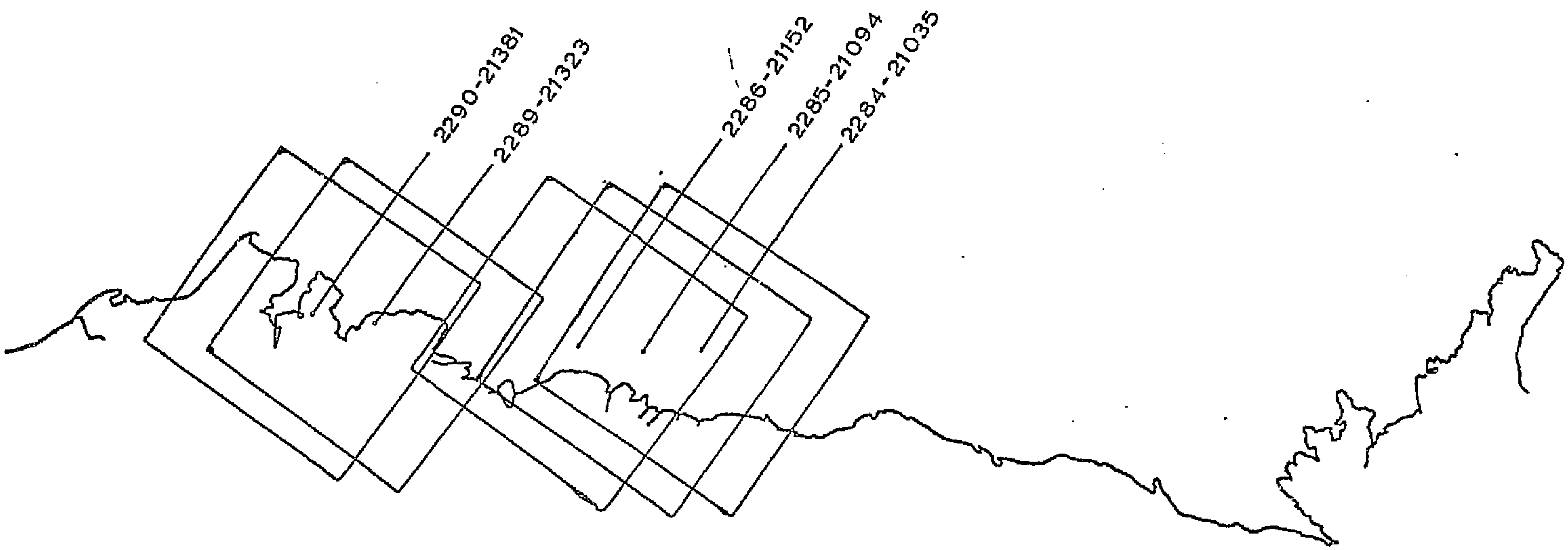
II-10 BEAUFORT SEA
FEBRUARY 20 - MARCH 10, 1975
IMAGES: 1942 to 1960



II-11 BEAUFORT SEA
18 JUNE - 5 JULY 1975
Images: 2147-2164

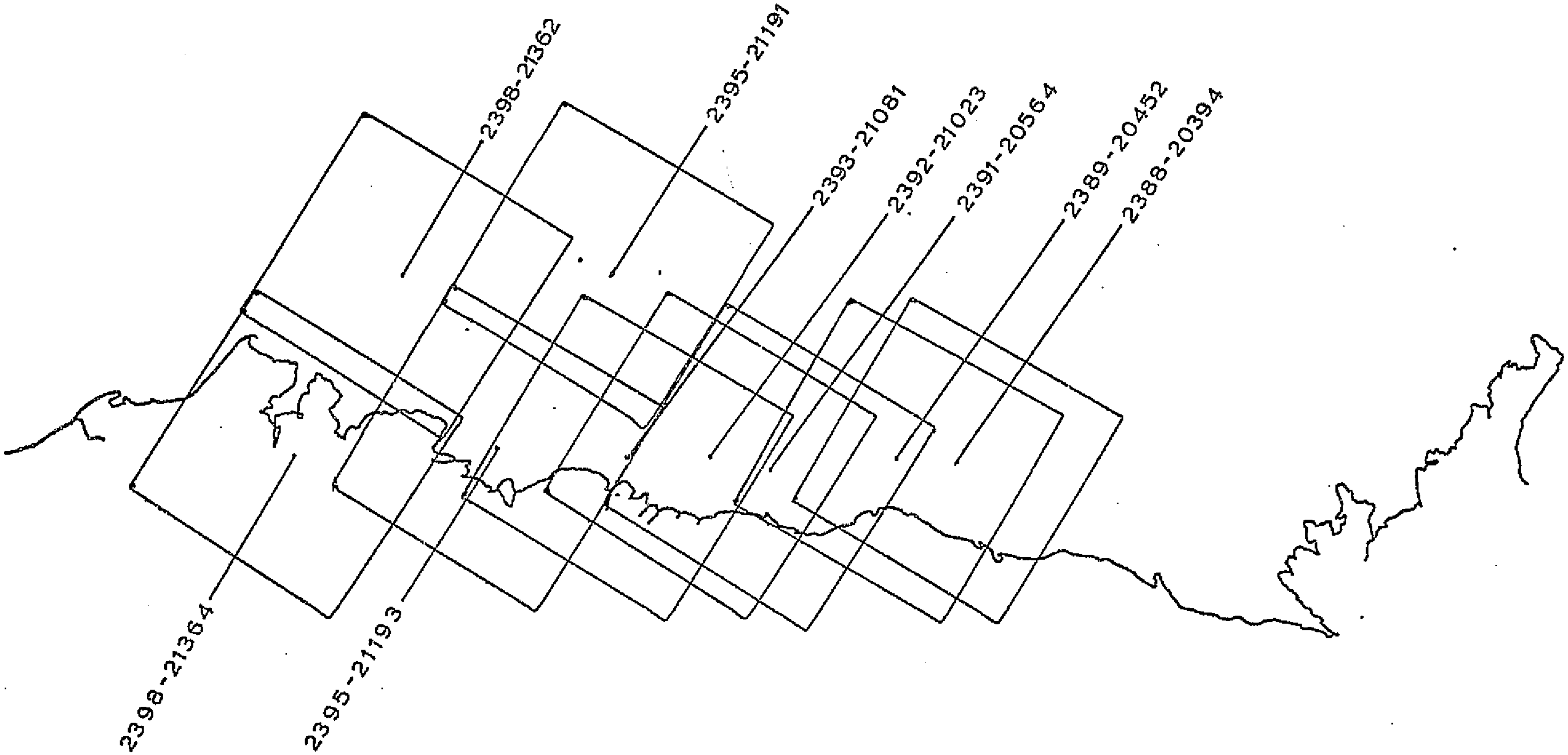


II-12 BEAUFORT SEA
6 JULY - 23 JULY 1975
Images 2165 - 2182



II-13 BEAUFORT SEA

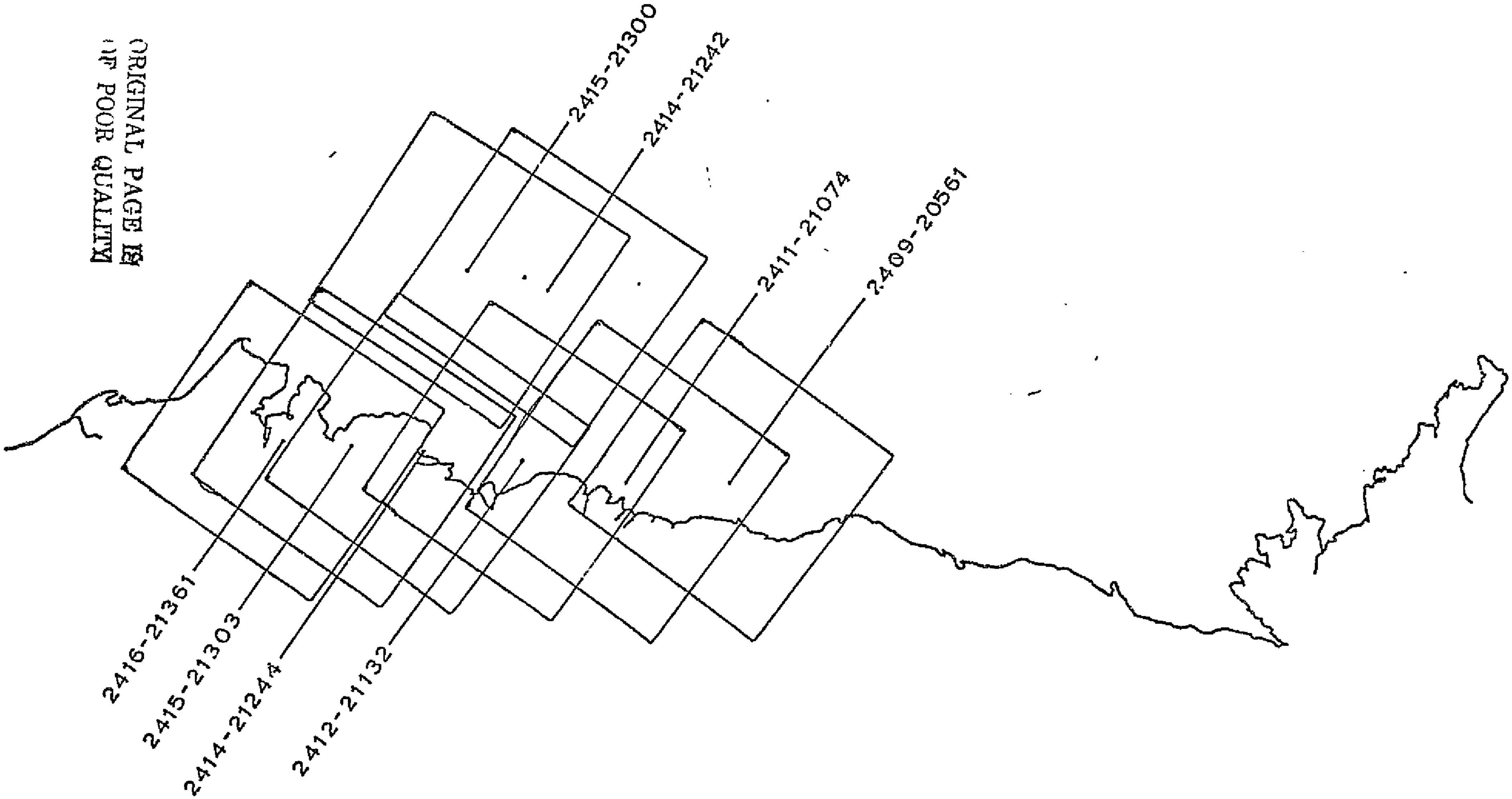
22 OCTOBER-8 NOVEMBER
1975
IMAGES: 2273-2290



II-14 BEAUFORT SEA

6 to 23 FEBRUARY 1976

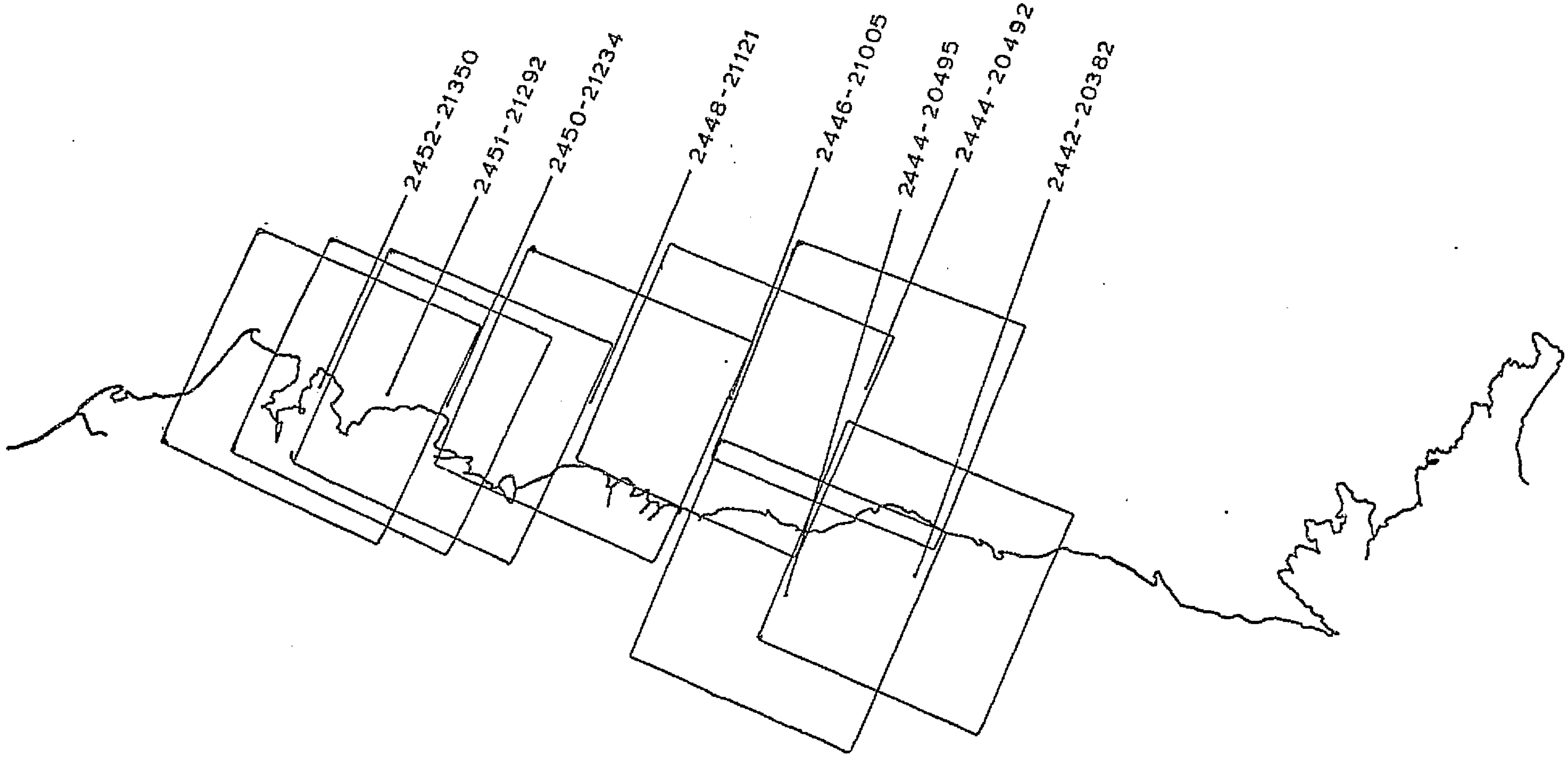
IMAGES: 2381-2398



II-15 BEAUFORT SEA

24 FEBRUARY to 12 MARCH 1976

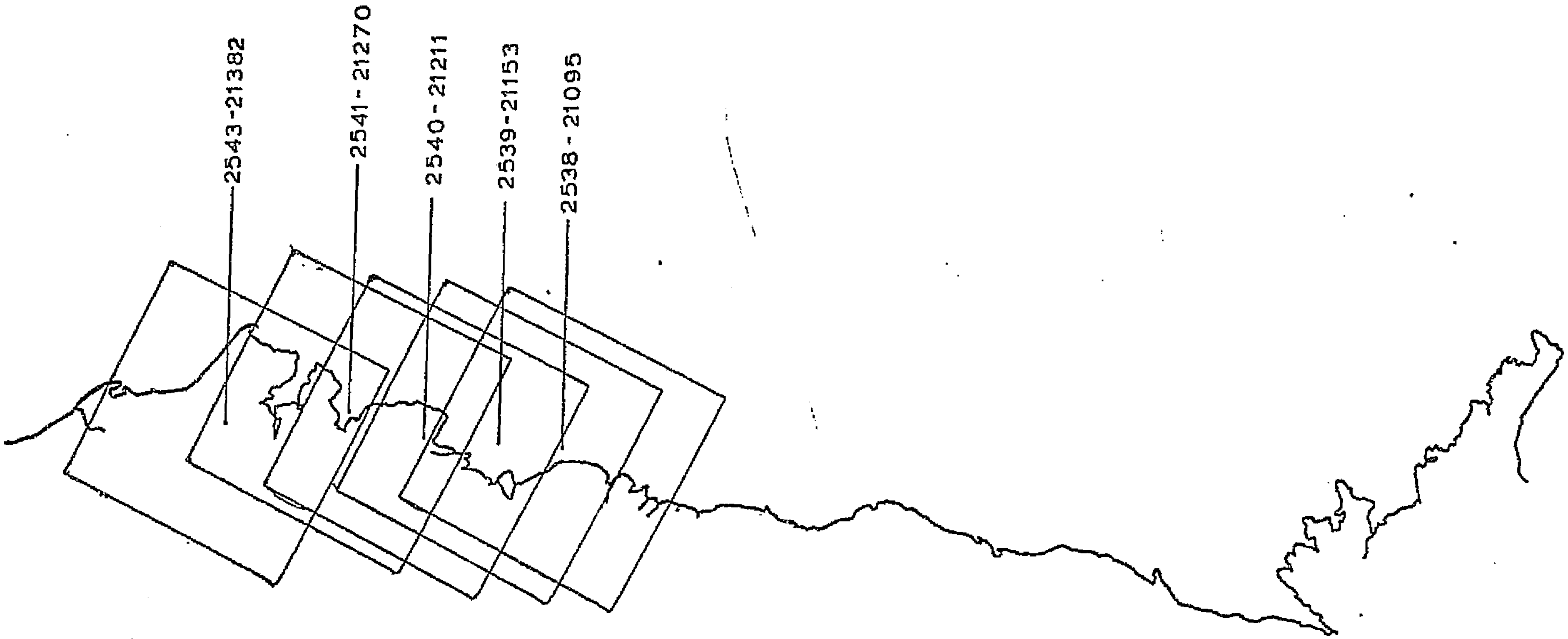
IMAGES: 2399-2416



II-16 BEAUFORT SEA

31 MARCH to 17 APRIL 1976

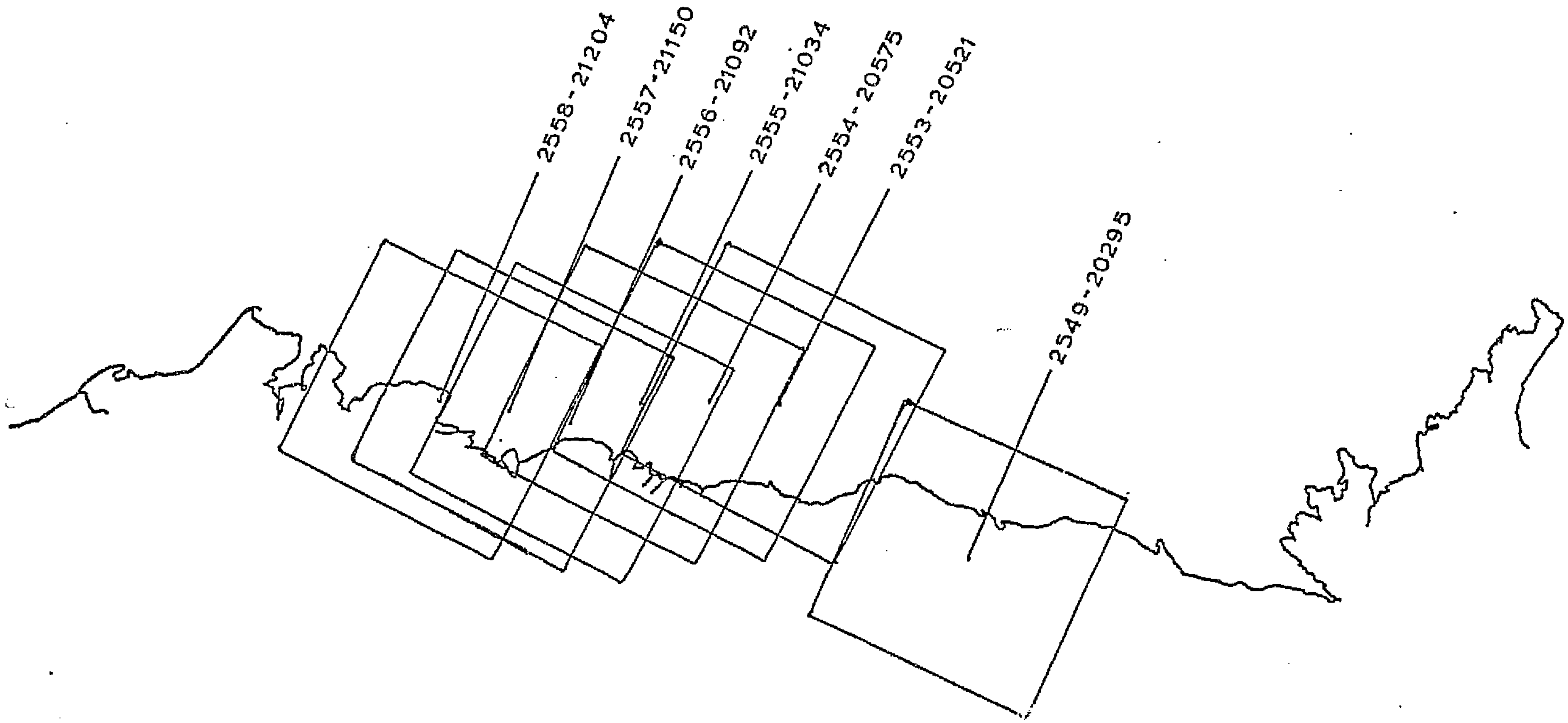
IMAGES: 2435-2452



II-17 BEAUFORT SEA

30 JUNE - 17 JULY 1976

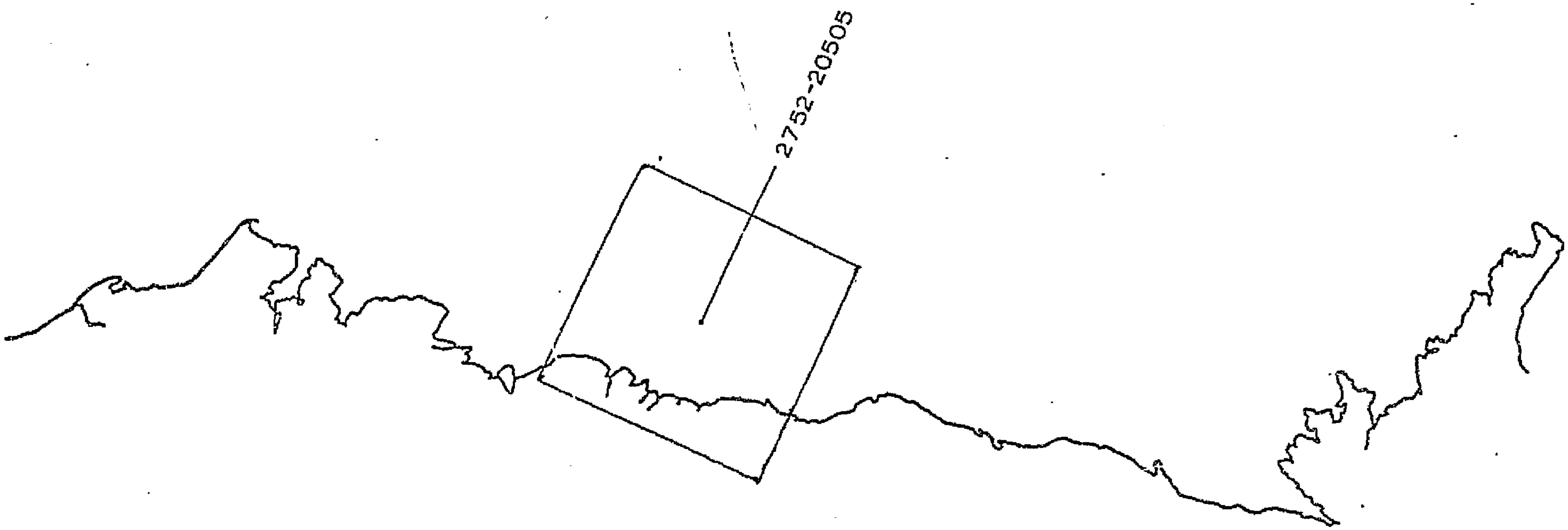
IMAGES: 2525 - 2542



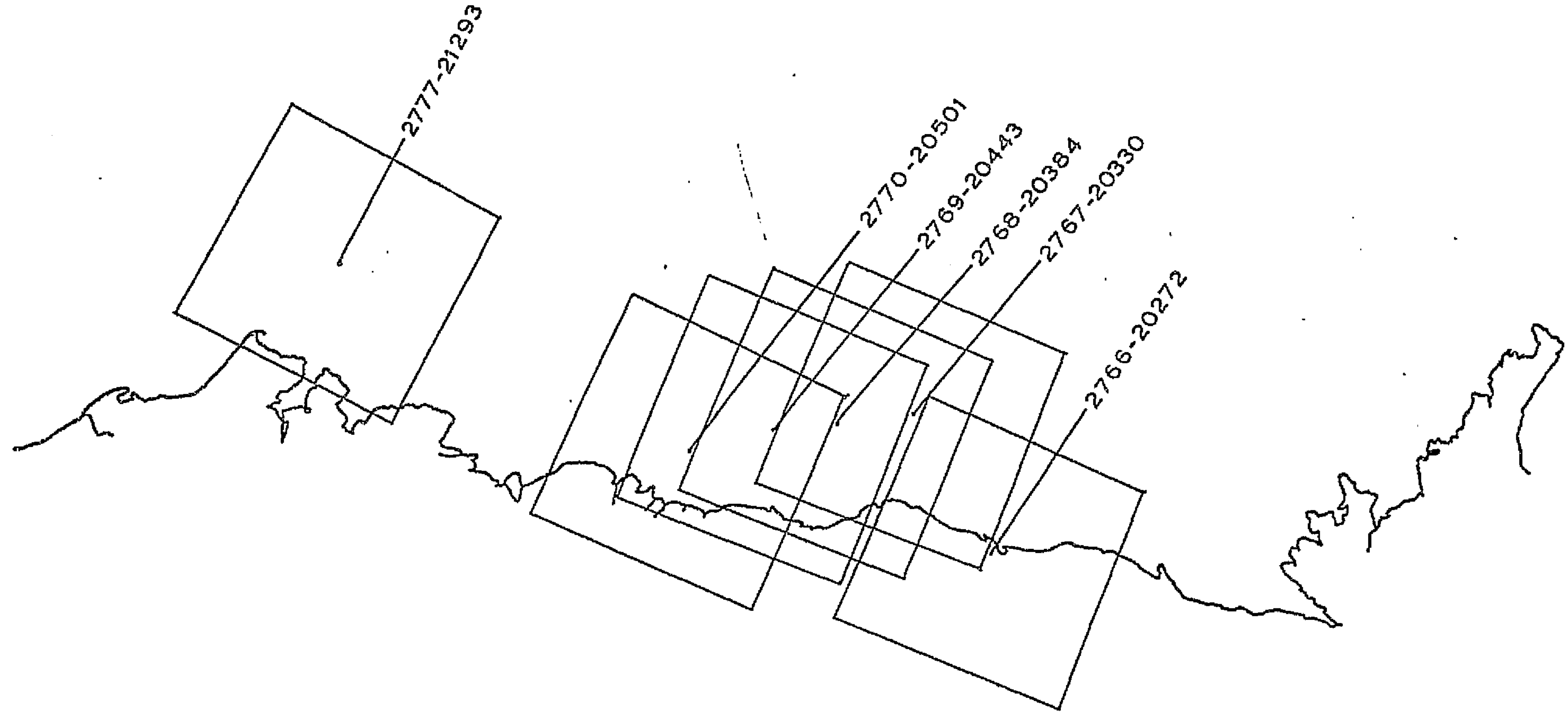
II-18 BEAUFORT SEA

18 JULY to 4 AUGUST 1976

IMAGES: 2543-2560



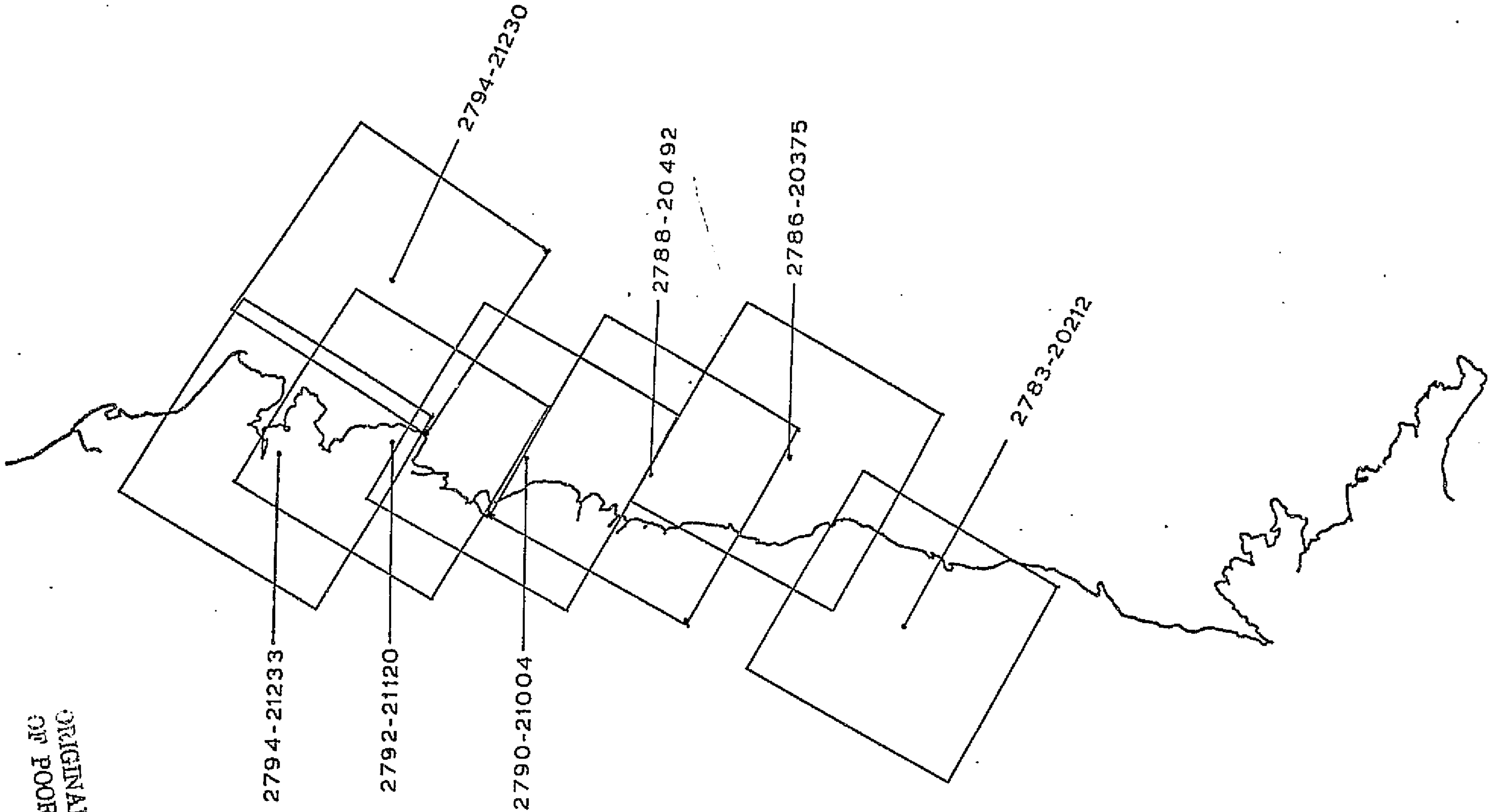
II-19 BEAUFORT SEA
1-18 FEBRUARY 1977
CYCLE 2741-2758



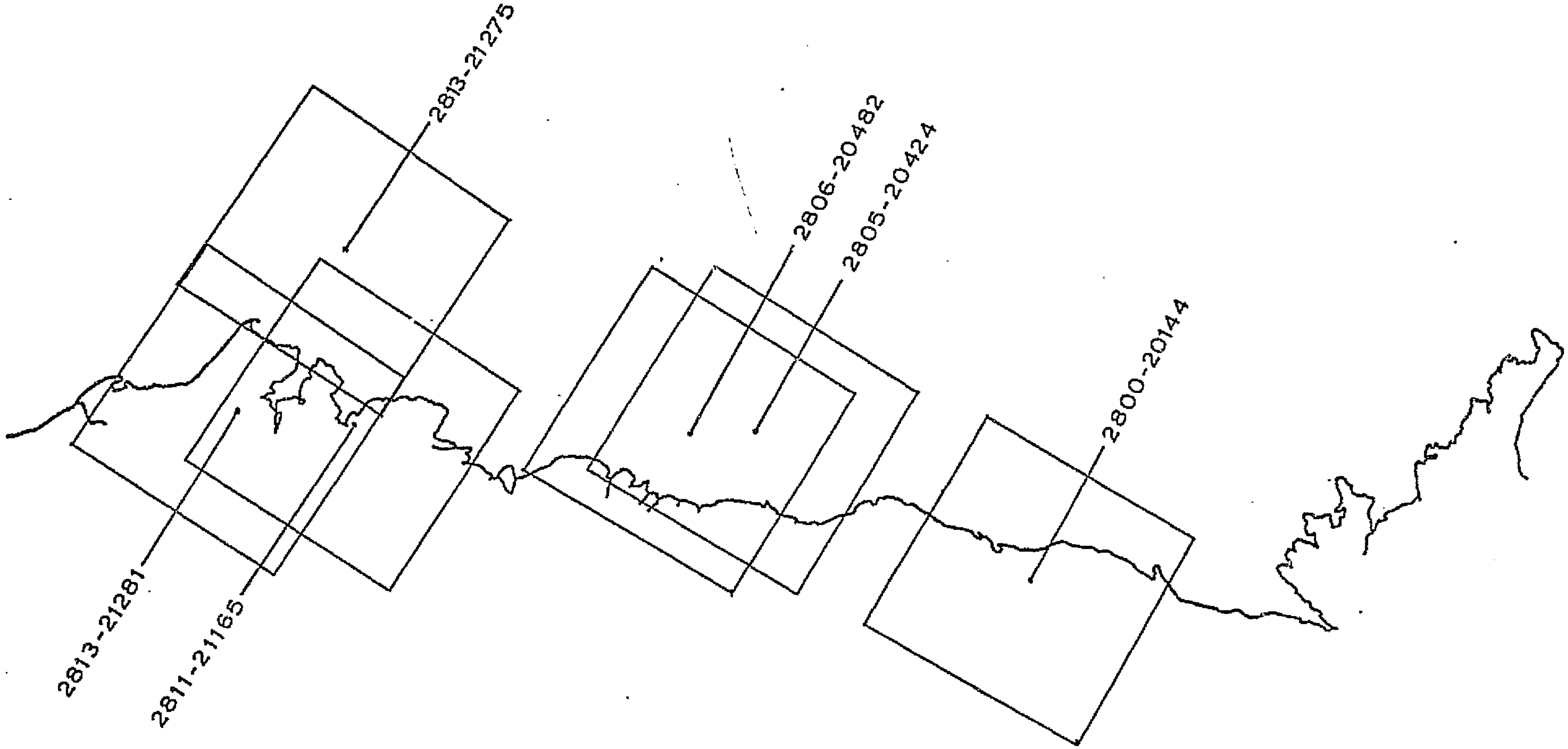
II-20 BEAUFORT SEA

19 FEBRUARY - 8 MARCH 1977

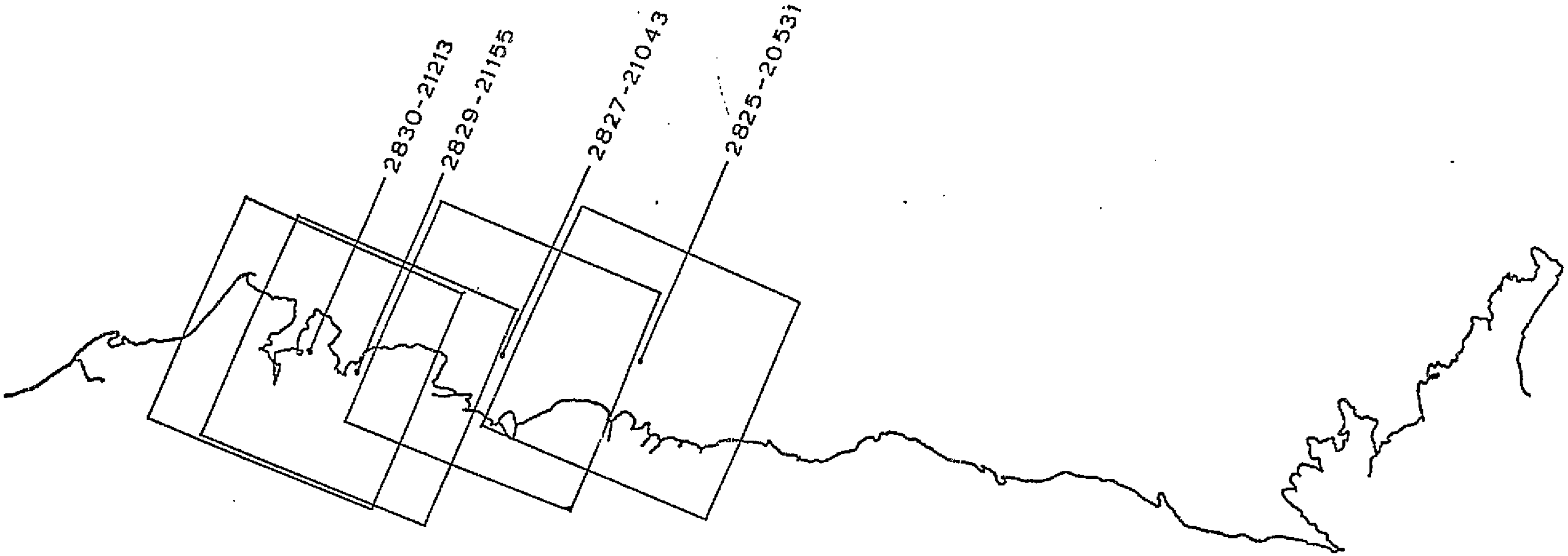
CYCLE 2759-2776



II-21 BEAUFORT SEA
9-26 MARCH 1977
CYCLE 2777-2794



II-22 BEAUFORT SEA
27 MARCH -13 APRIL 1977
CYCLE 2795-2812



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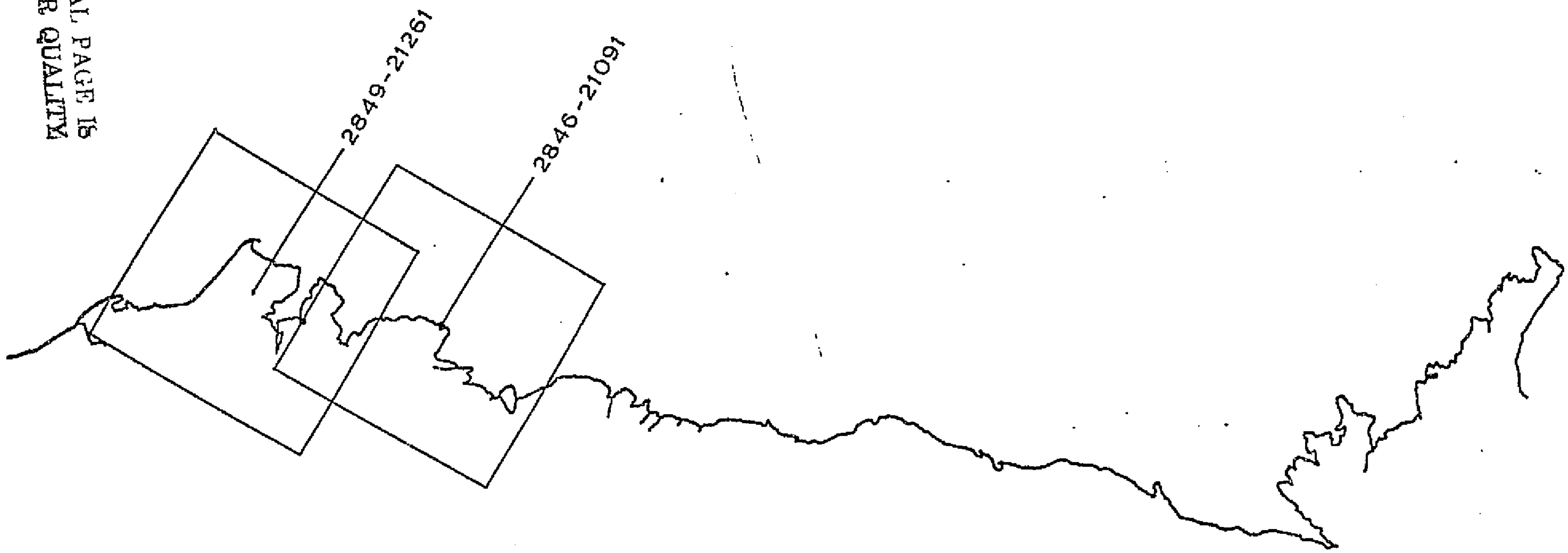
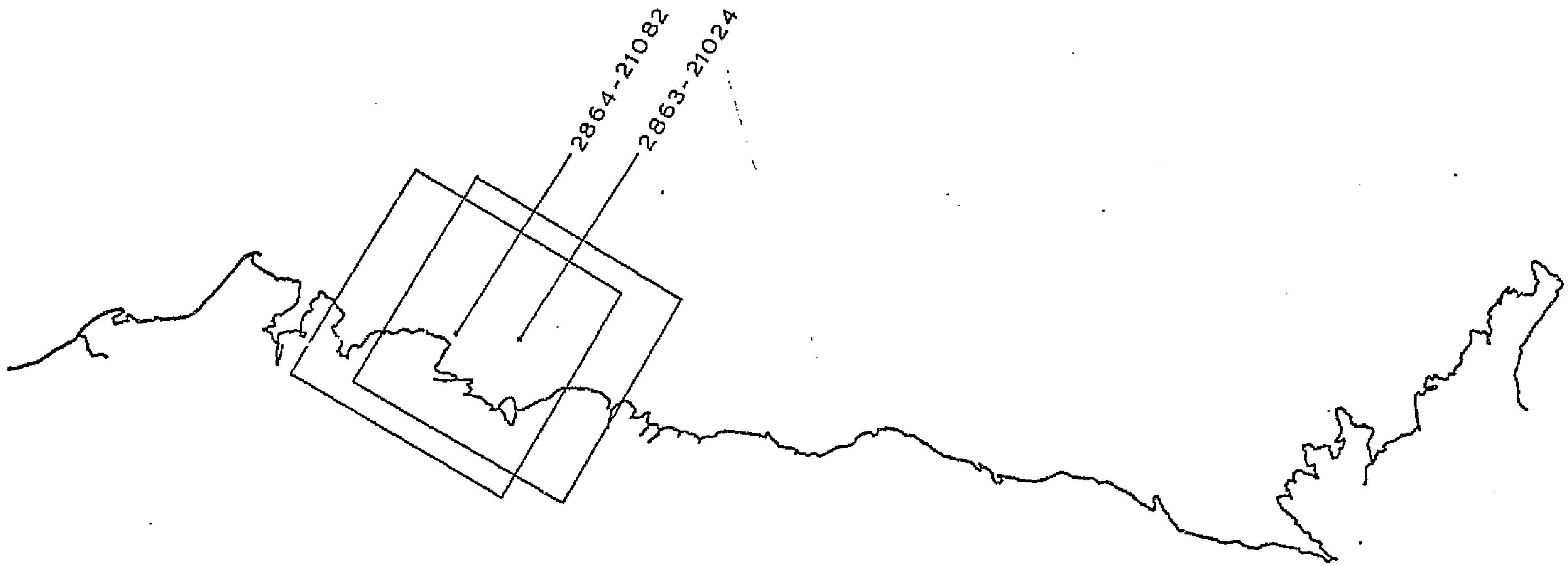
II-23 BEAUFORT SEA
14 APRIL-1 MAY 1977
CYCLE 2813-2830



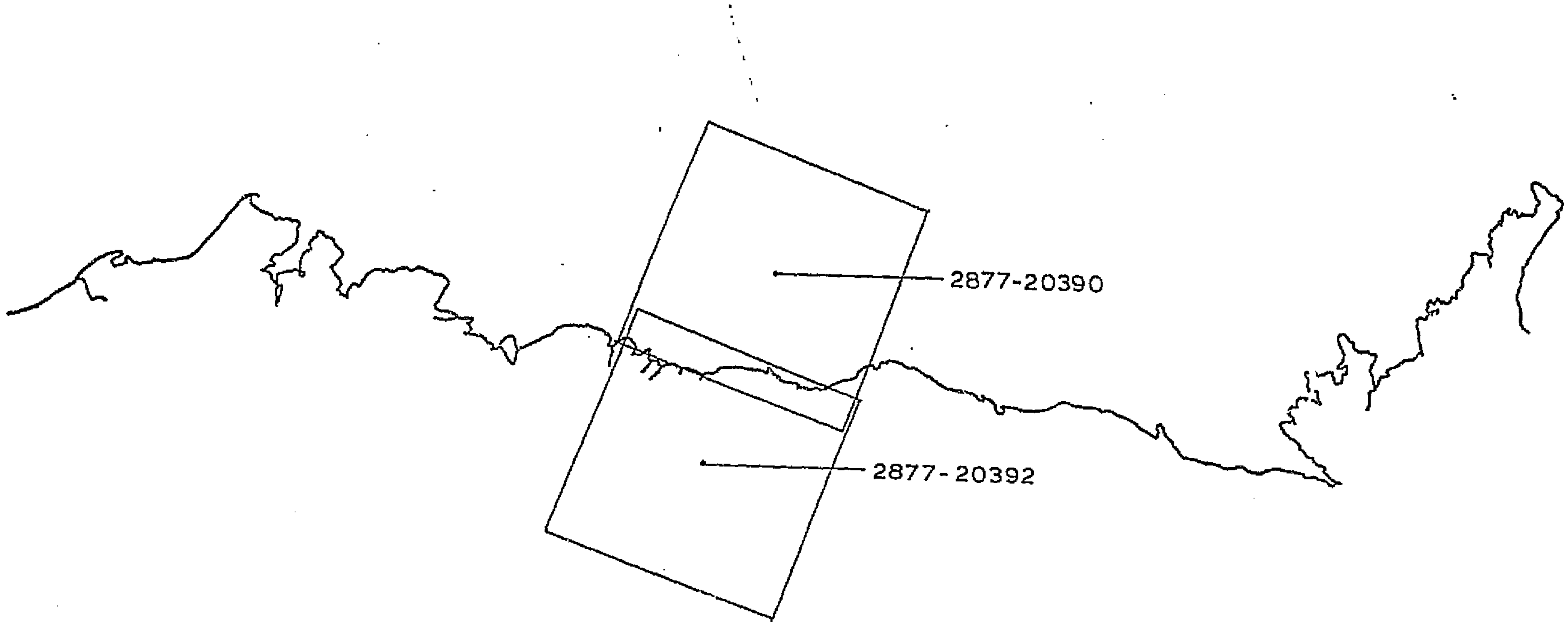
II-24 BEAUFORT SEA
2-19 MAY 1977
CYCLE 2831-2848



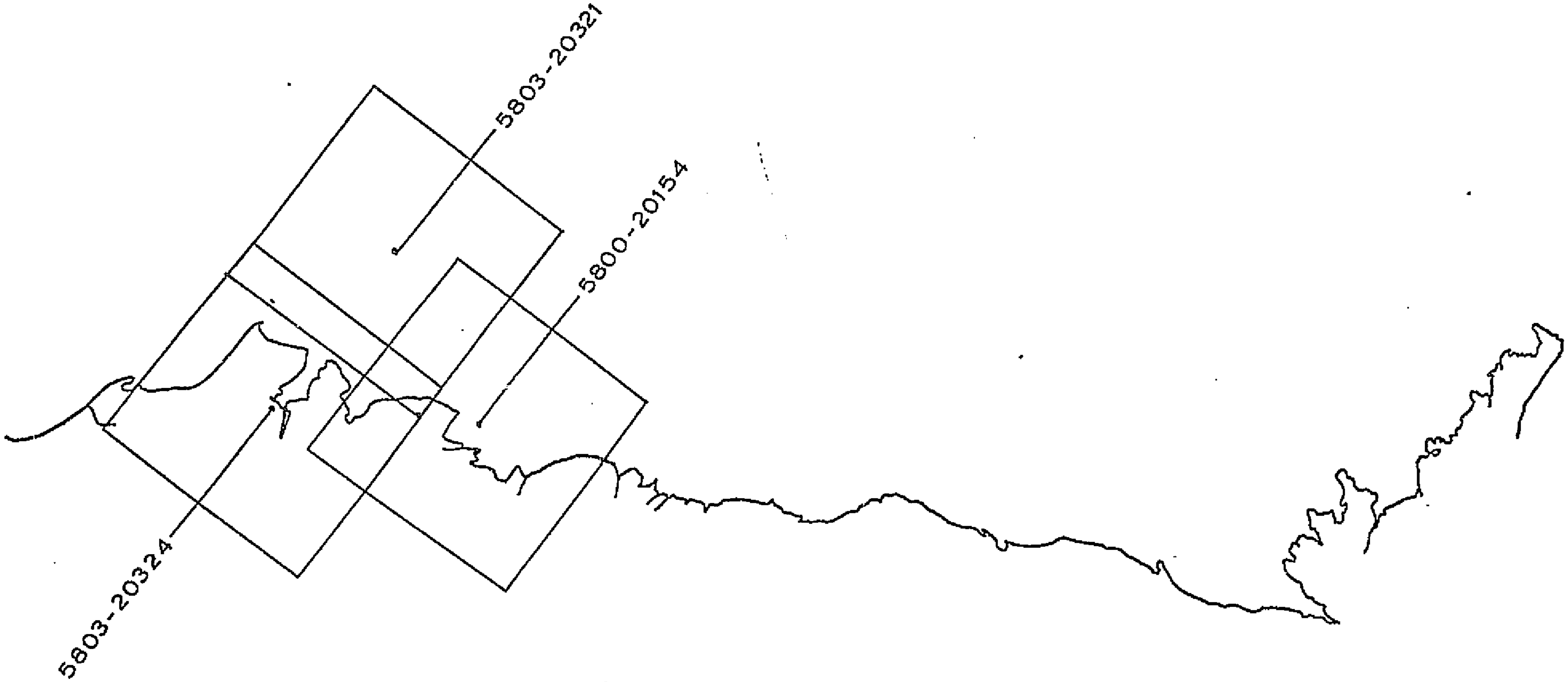
II-25 BEAUFORT SEA

20 MAY - 6 JUNE 1977

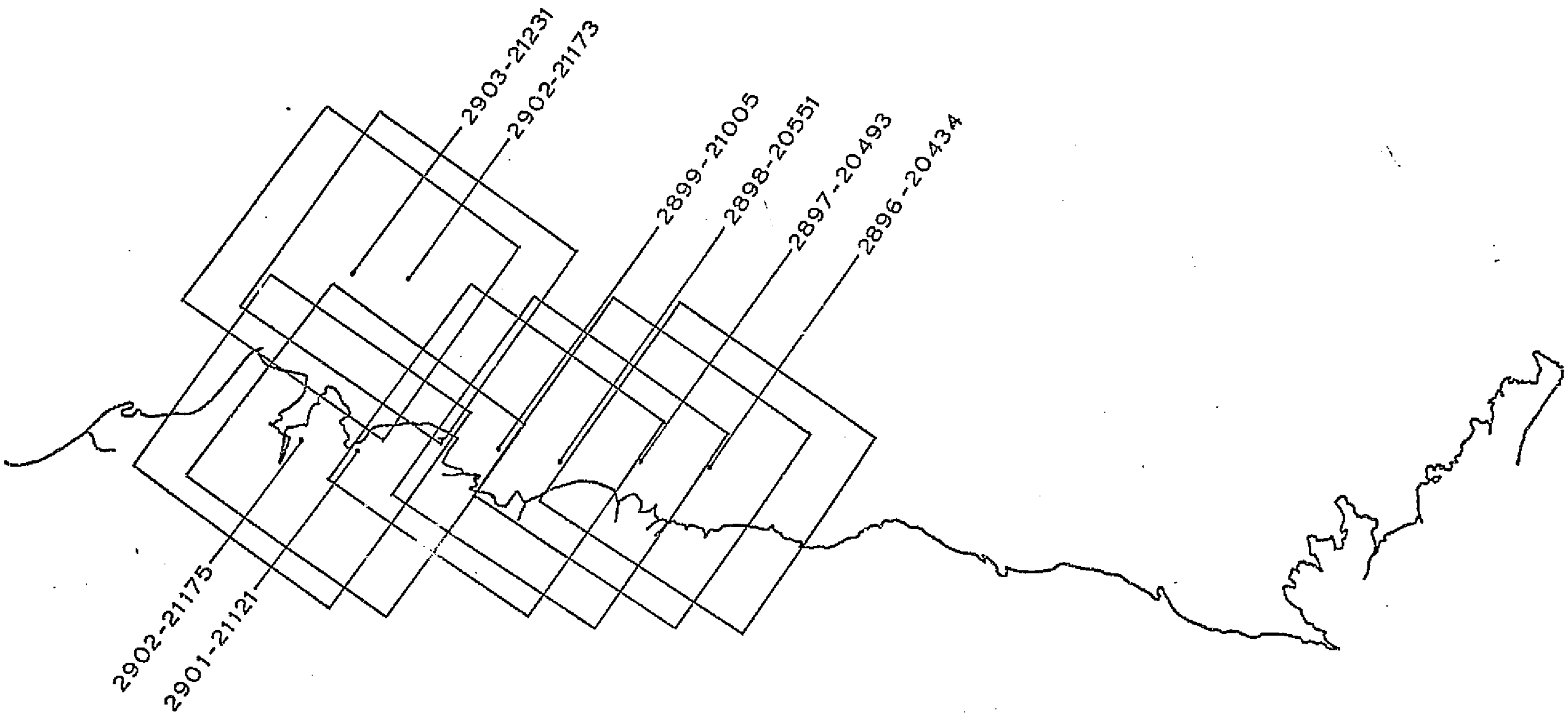
CYCLE 2849 - 2866



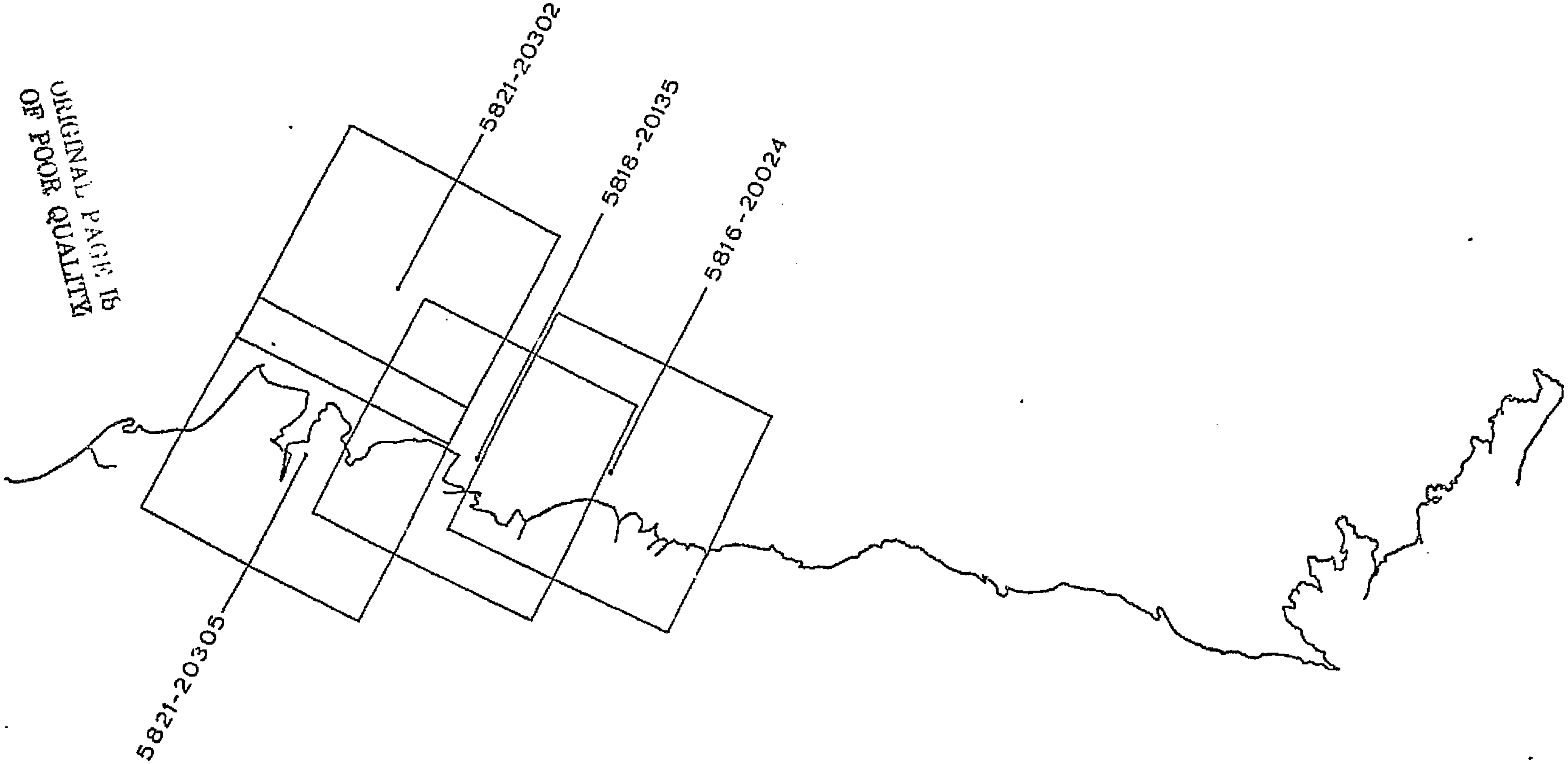
II-26 BEAUFORT SEA
7-24 JUNE 1977
CYCLE 2867-2884



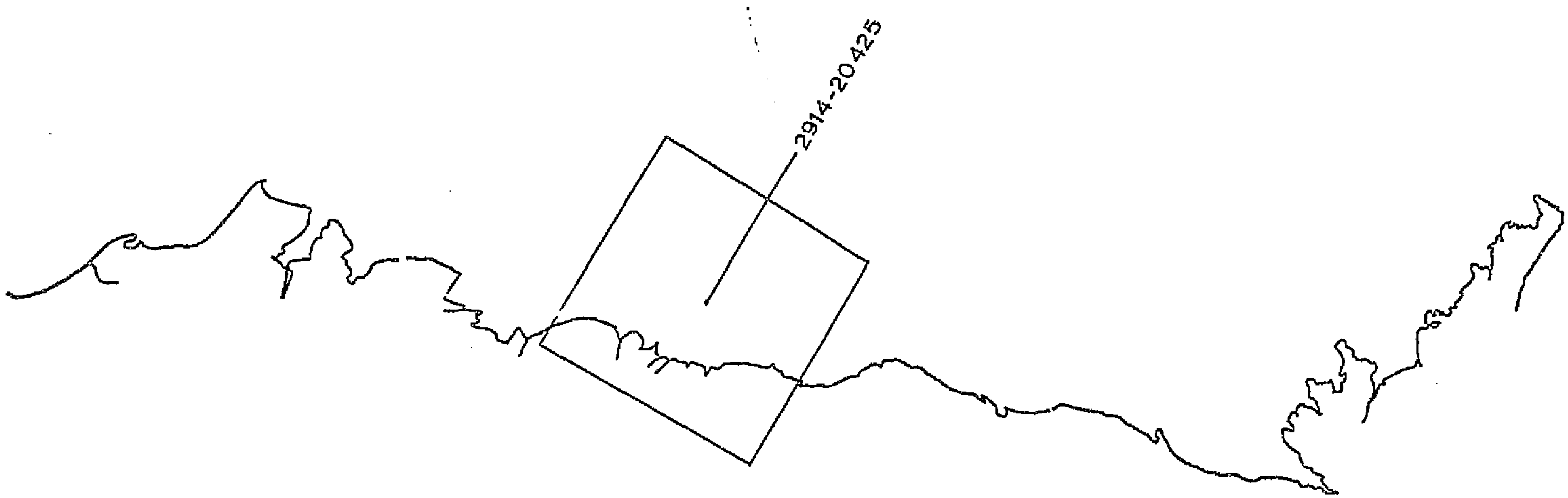
II-27 BEAUFORT SEA
13-30 JUNE 1977
CYCLE 5786-5803



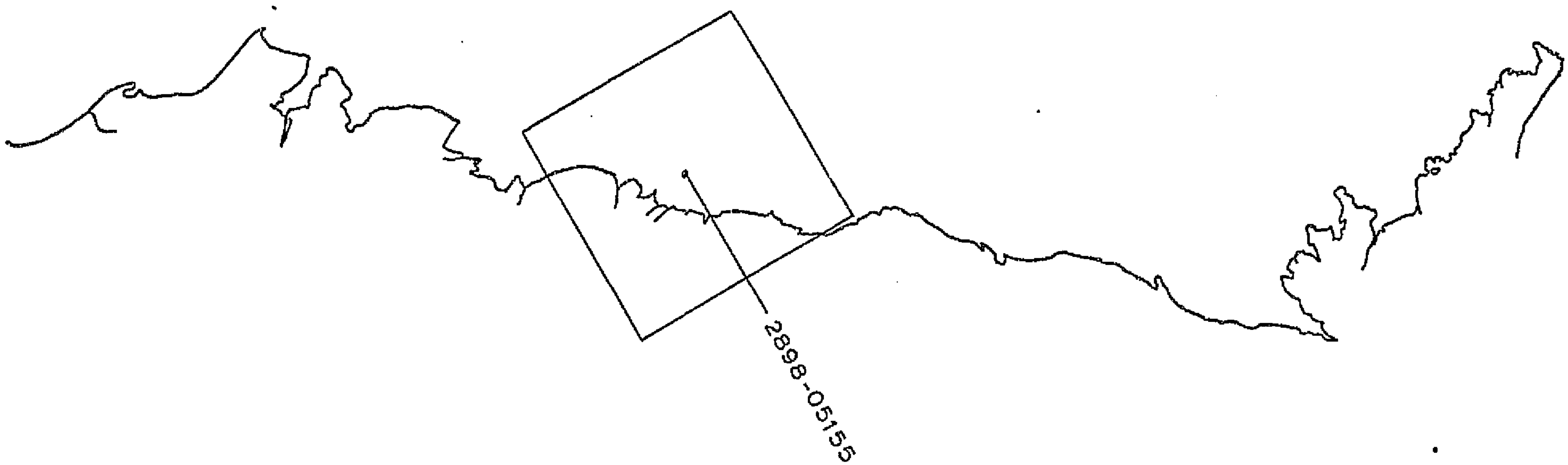
II-28 BEAUFORT SEA
25 JUNE-12 JULY 1977
CYCLE 2885-2902



II-29 BEAUFORT SEA
1-18 JULY 1977
CYCLE 5804-5821



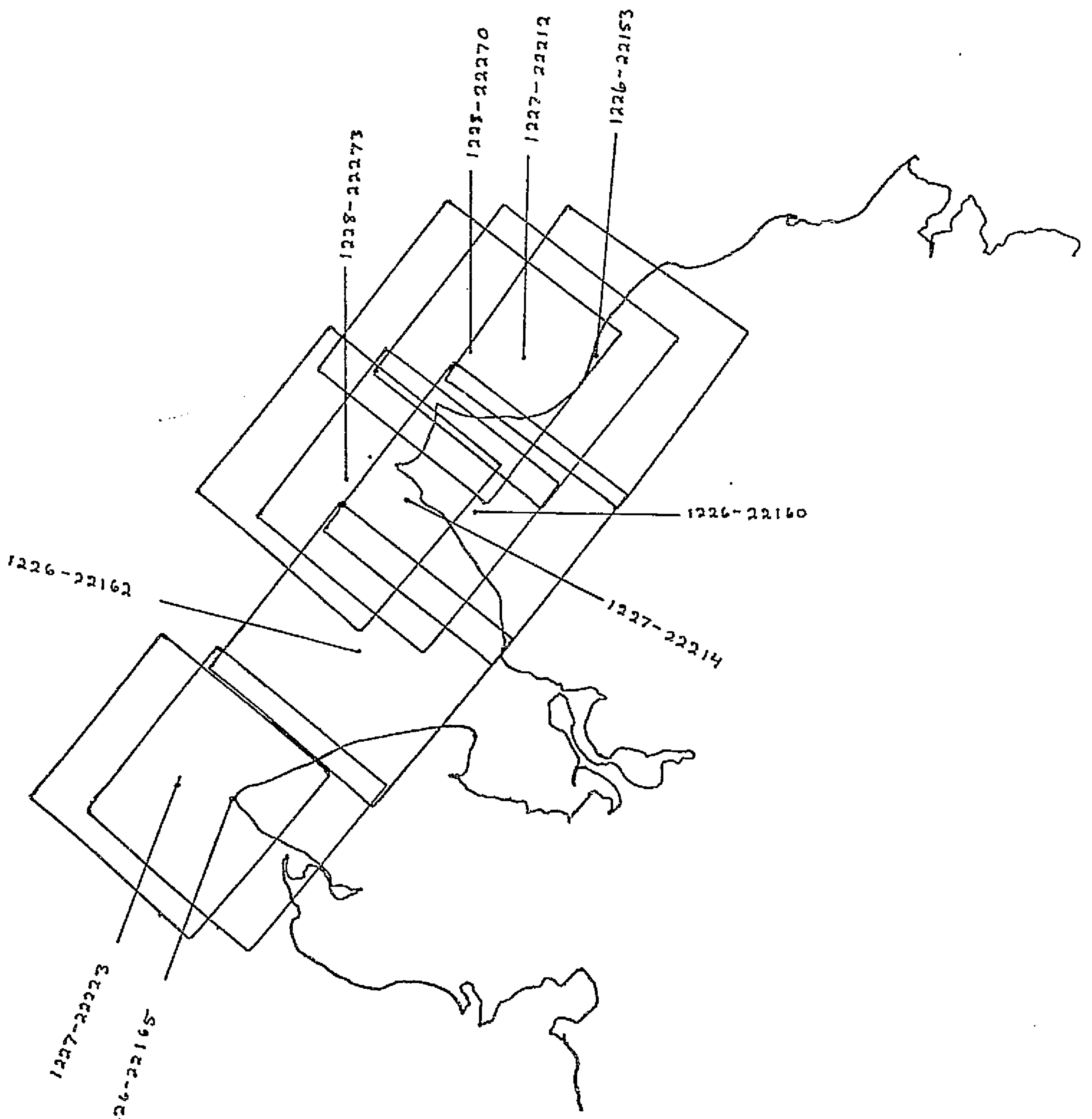
II-30 BEAUFORT SEA
13-30 JULY 1977
CYCLE 2903-2920



II-31 BEAUFORT SEA
ASCENDING NODE
8 JULY 1977

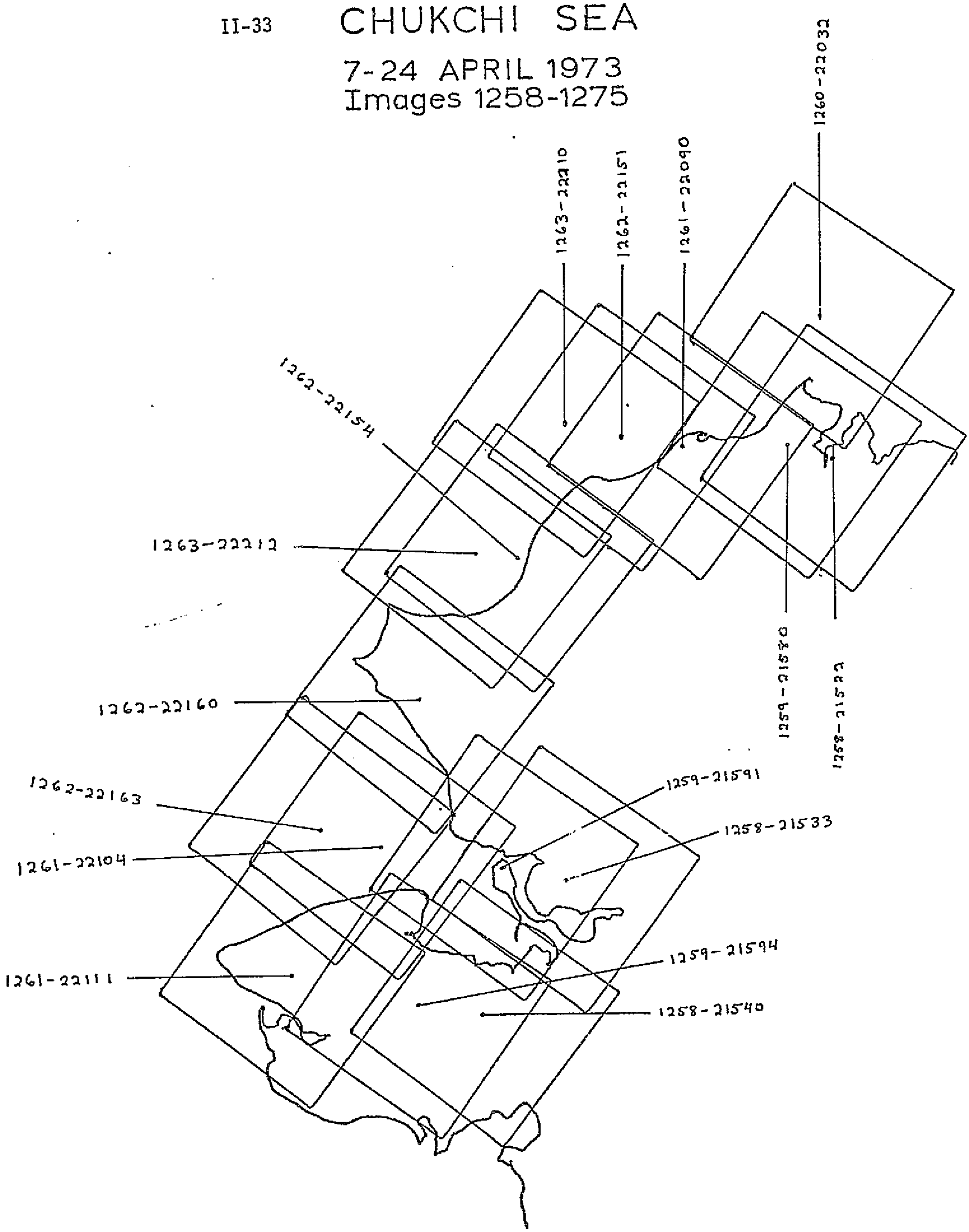
CHUKCHI SEA

2-19 MARCH 1973
Images 1222-1239



CHUKCHI SEA

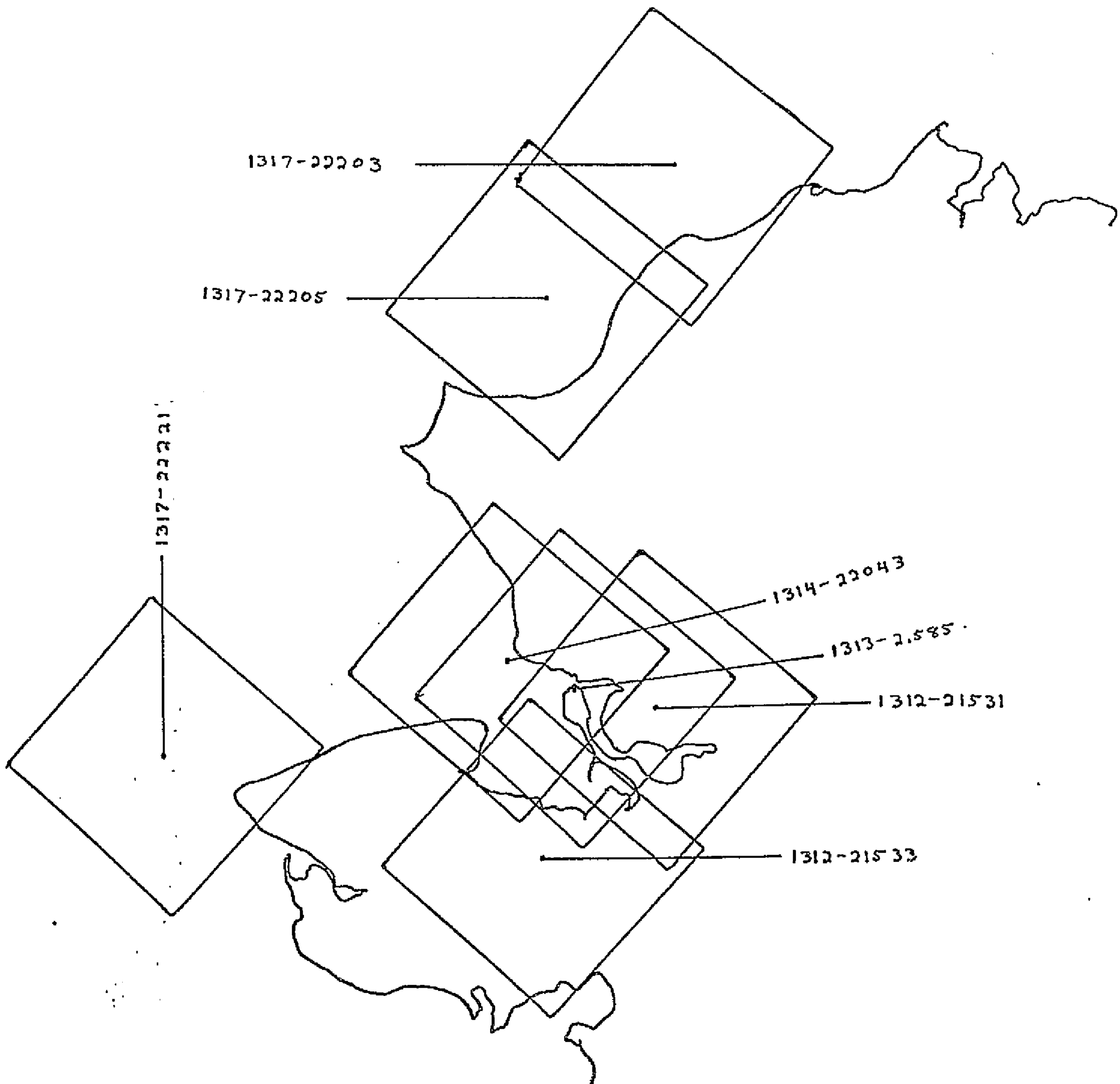
7-24 APRIL 1973
Images 1258-1275



II-34

CHUKCHI SEA

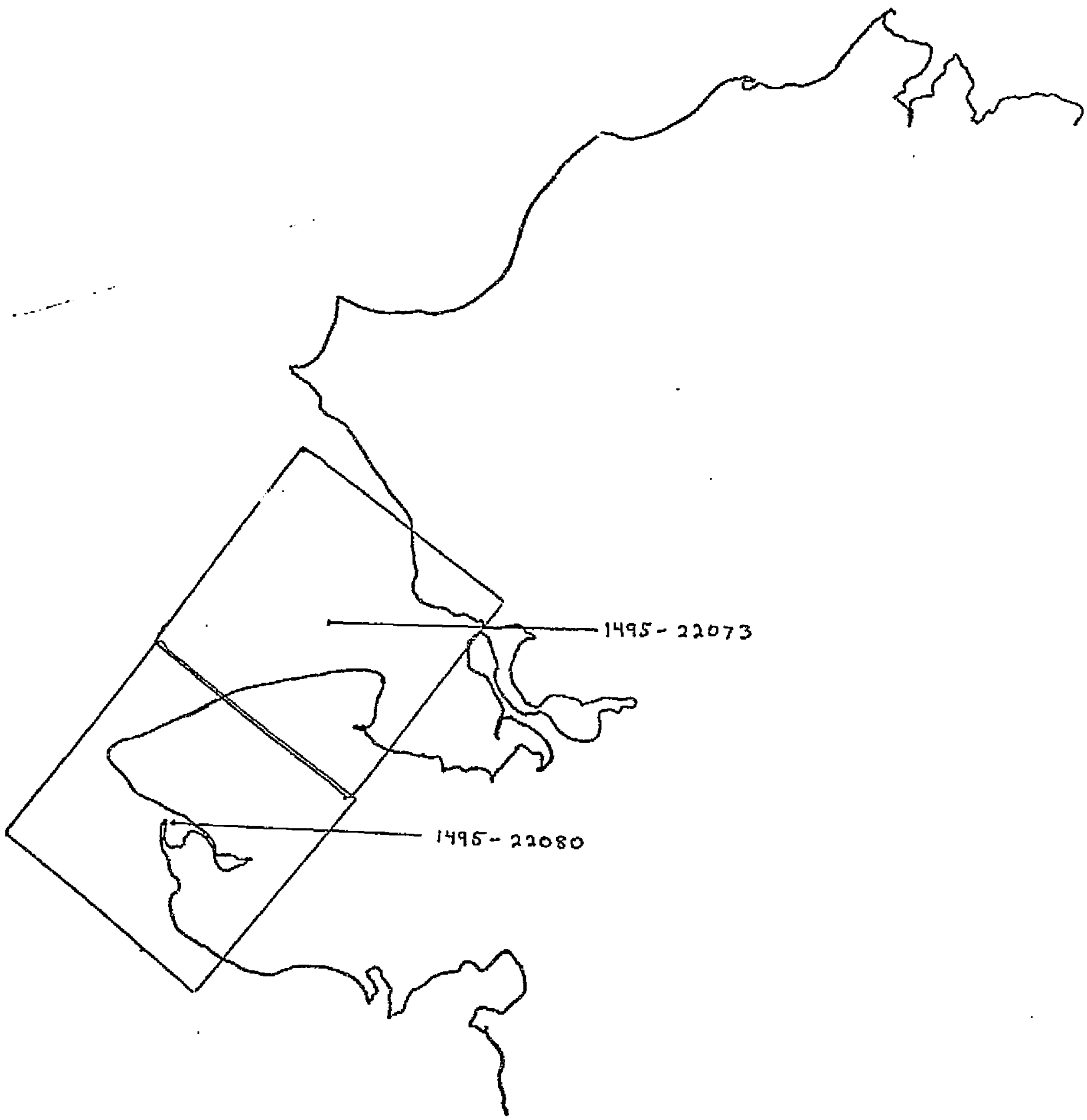
31 MAY-17 JUNE 1973
Images 1312-1329



CHUKCHI SEA

27 NOVEMBER-14 DECEMBER 1973

Images 1492-1509

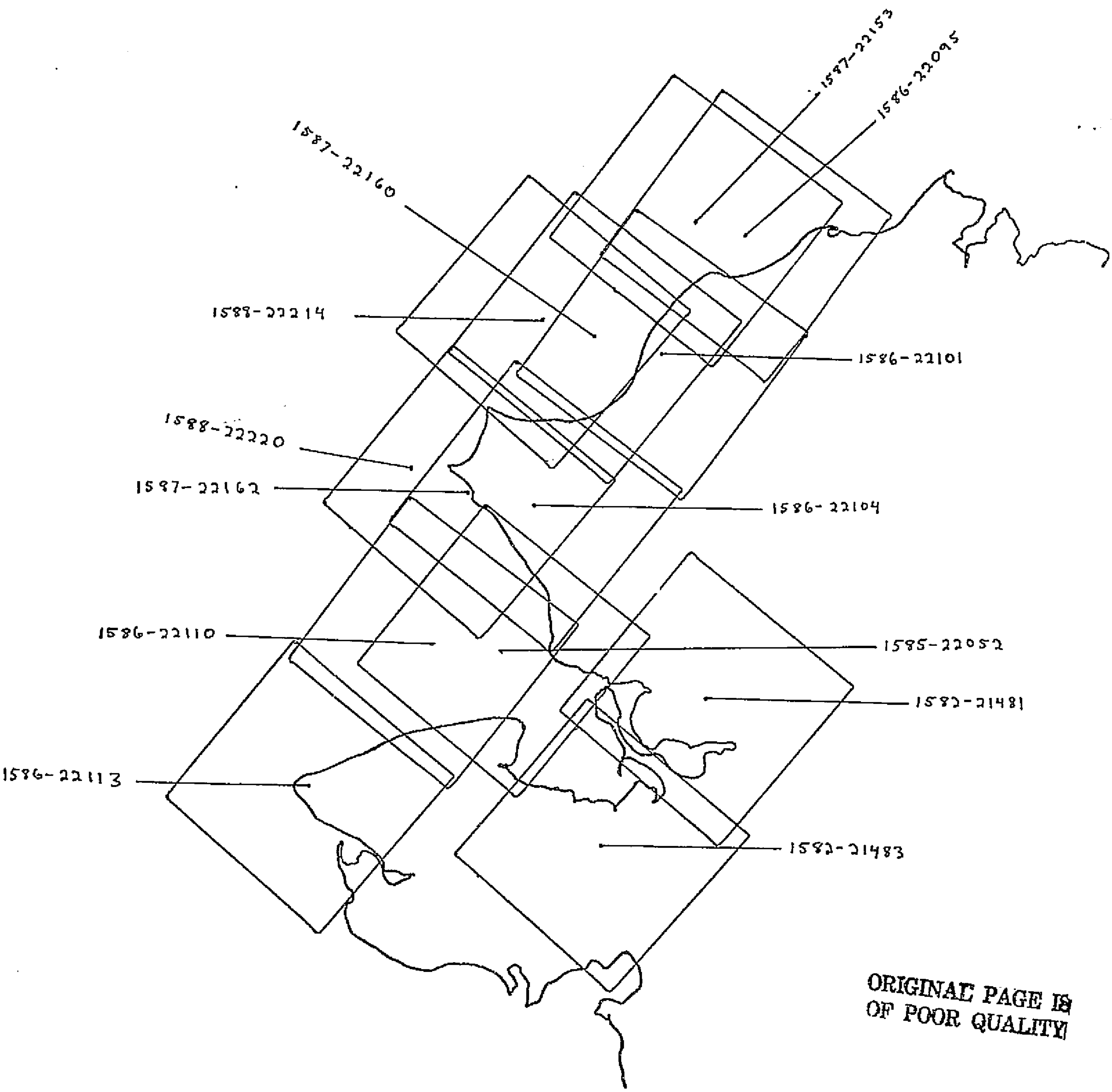


II-36

CHUKCHI SEA

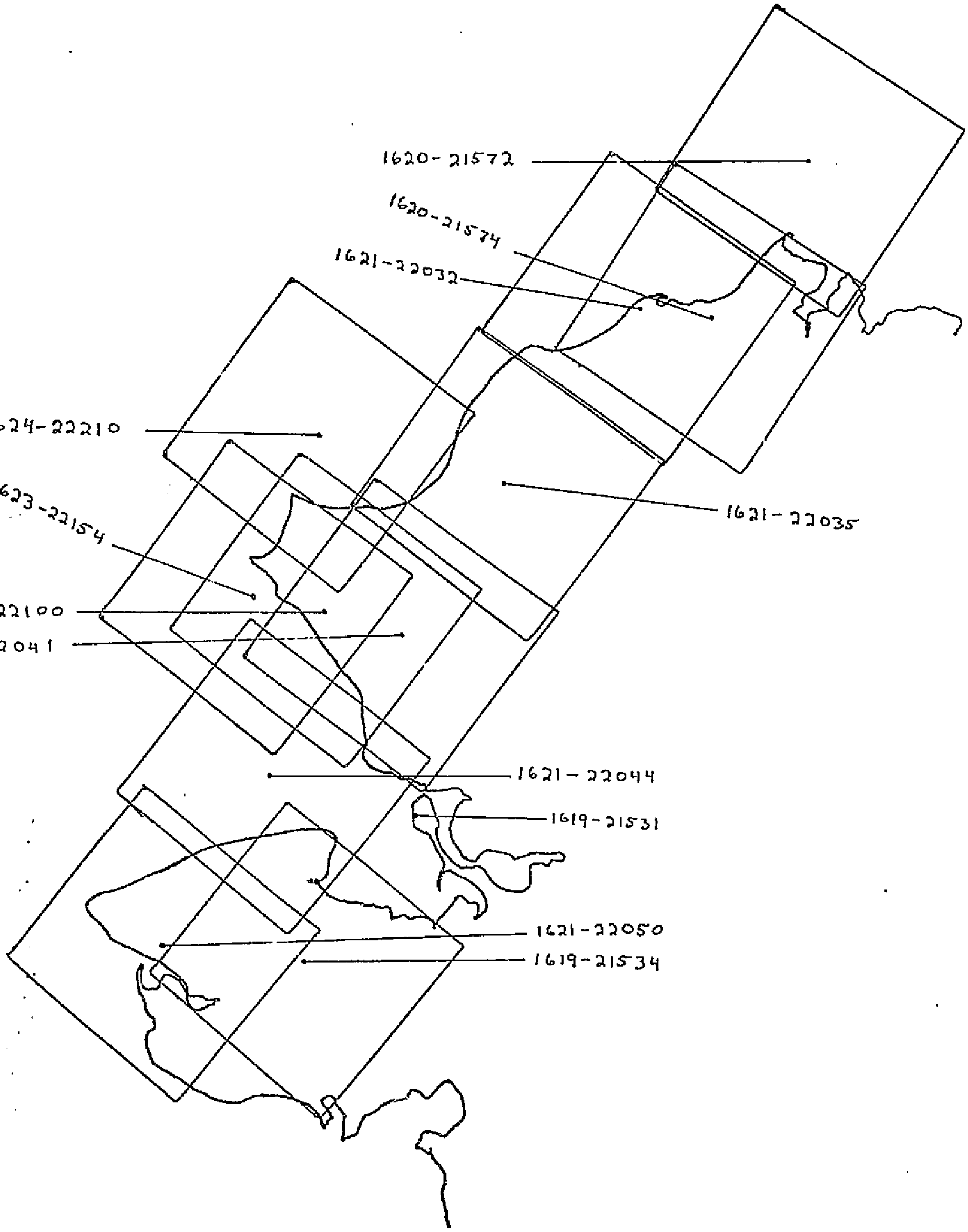
25 FEBRUARY-14 MARCH 1974

Cycle 1582-1599



II-37 CHUKCHI SEA

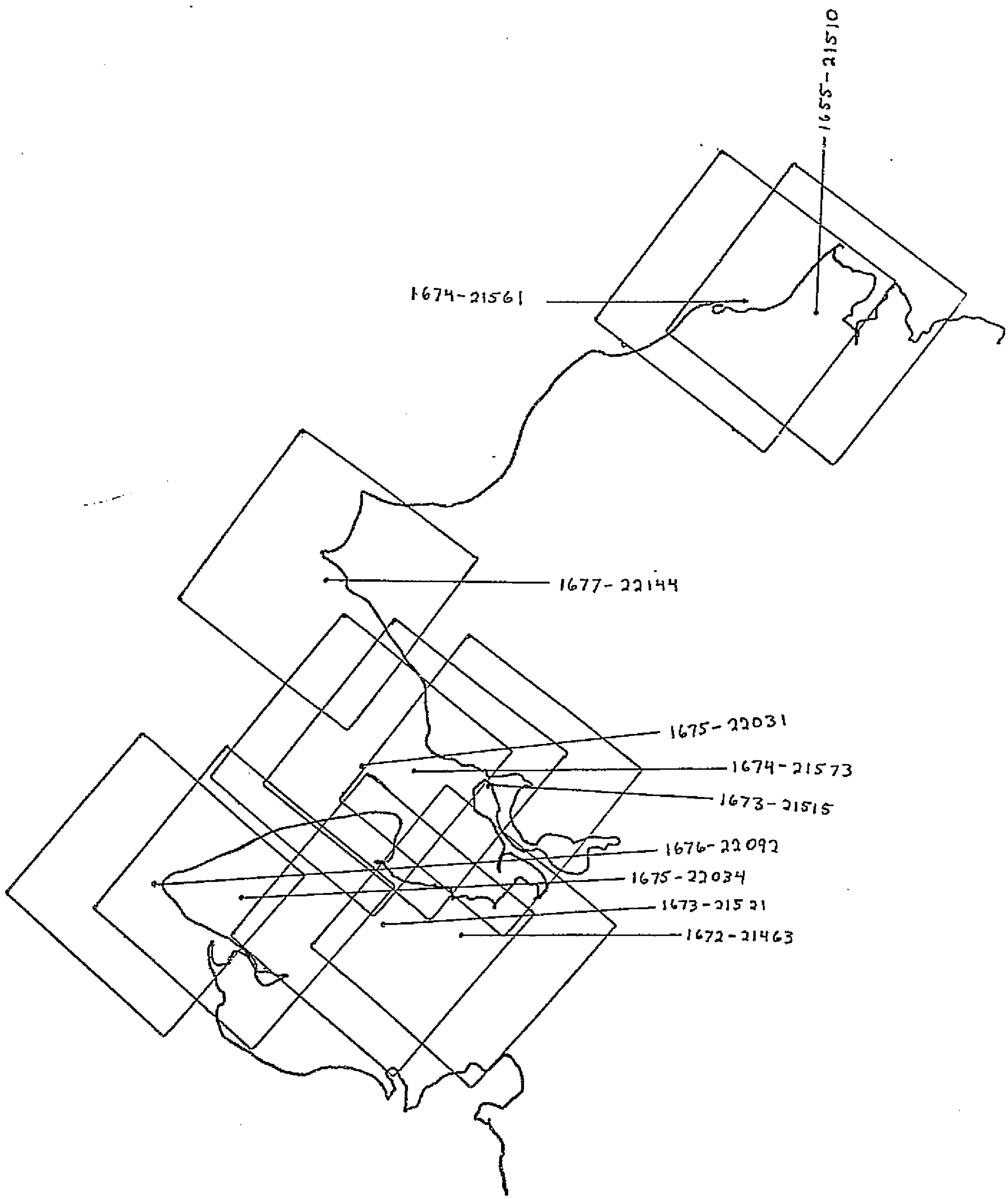
2-19 APRIL 1974
Cycle 1618-1635



II-38 CHUKCHI SEA

26 MAY-12 JUNE 1974

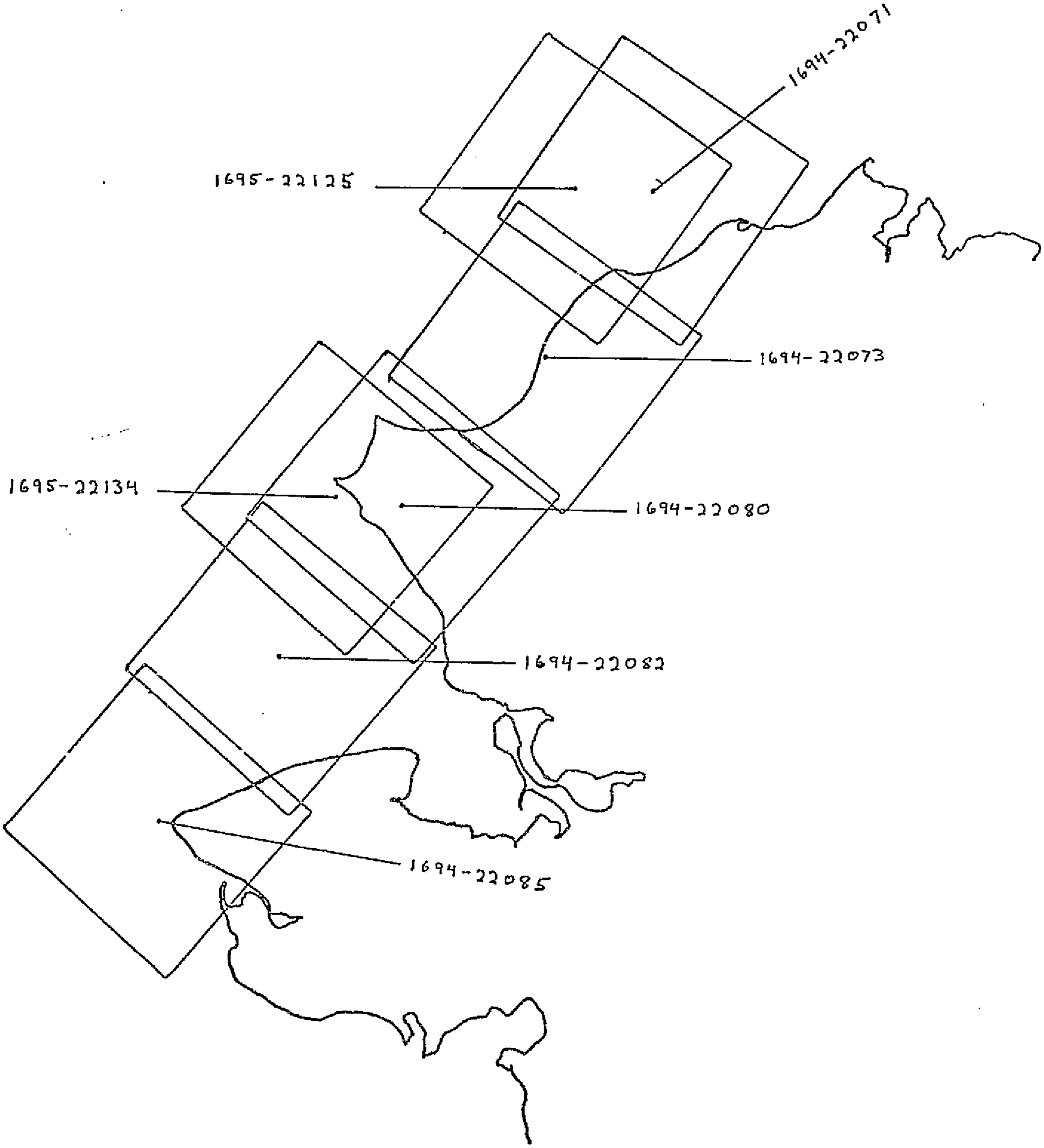
Cycle 1672 - 1689



II-39

CHUKCHI SEA

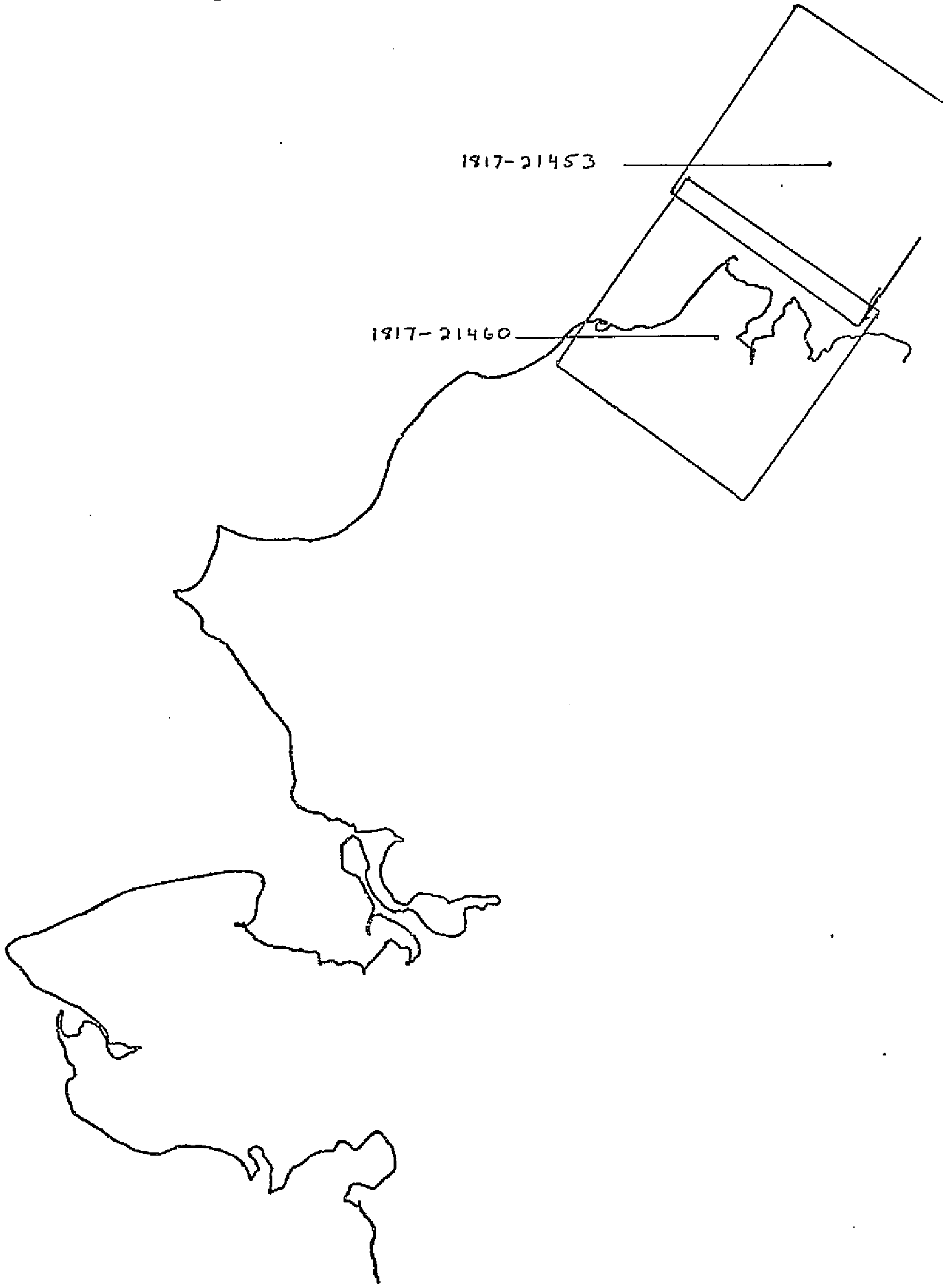
13-30 JUNE 1974
Cycle 1690-1707



CHUKCHI SEA

17 OCTOBER-3 NOVEMBER 1974

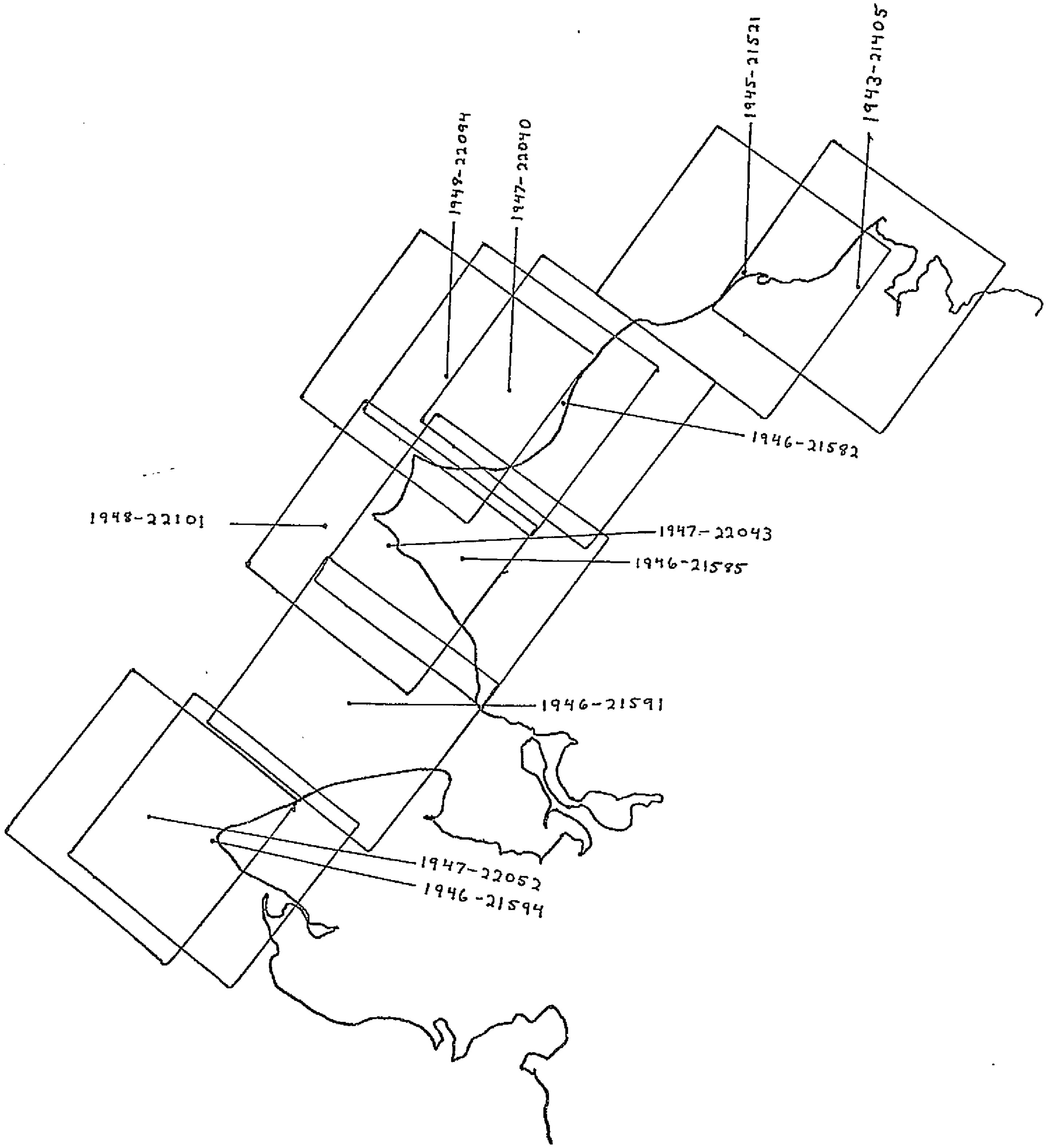
Cycle 1816-1833



II-41 CHUKCHI SEA

20 FEBRUARY - 9 MARCH 1975

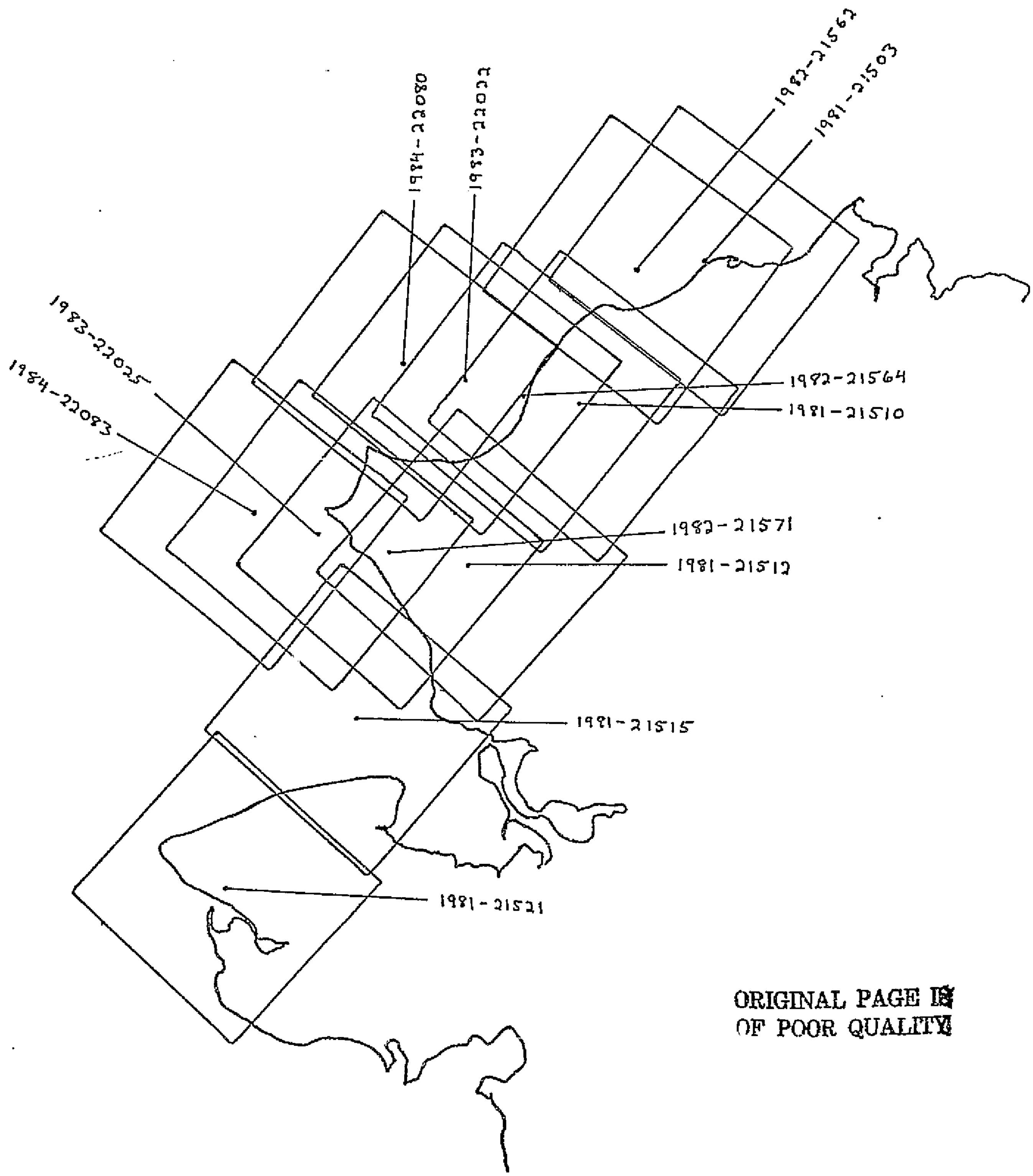
Cycle 1942-1959



II-42

CHUKCHI SEA

28 MARCH-14 APRIL 1975
Cycle 1978-1995



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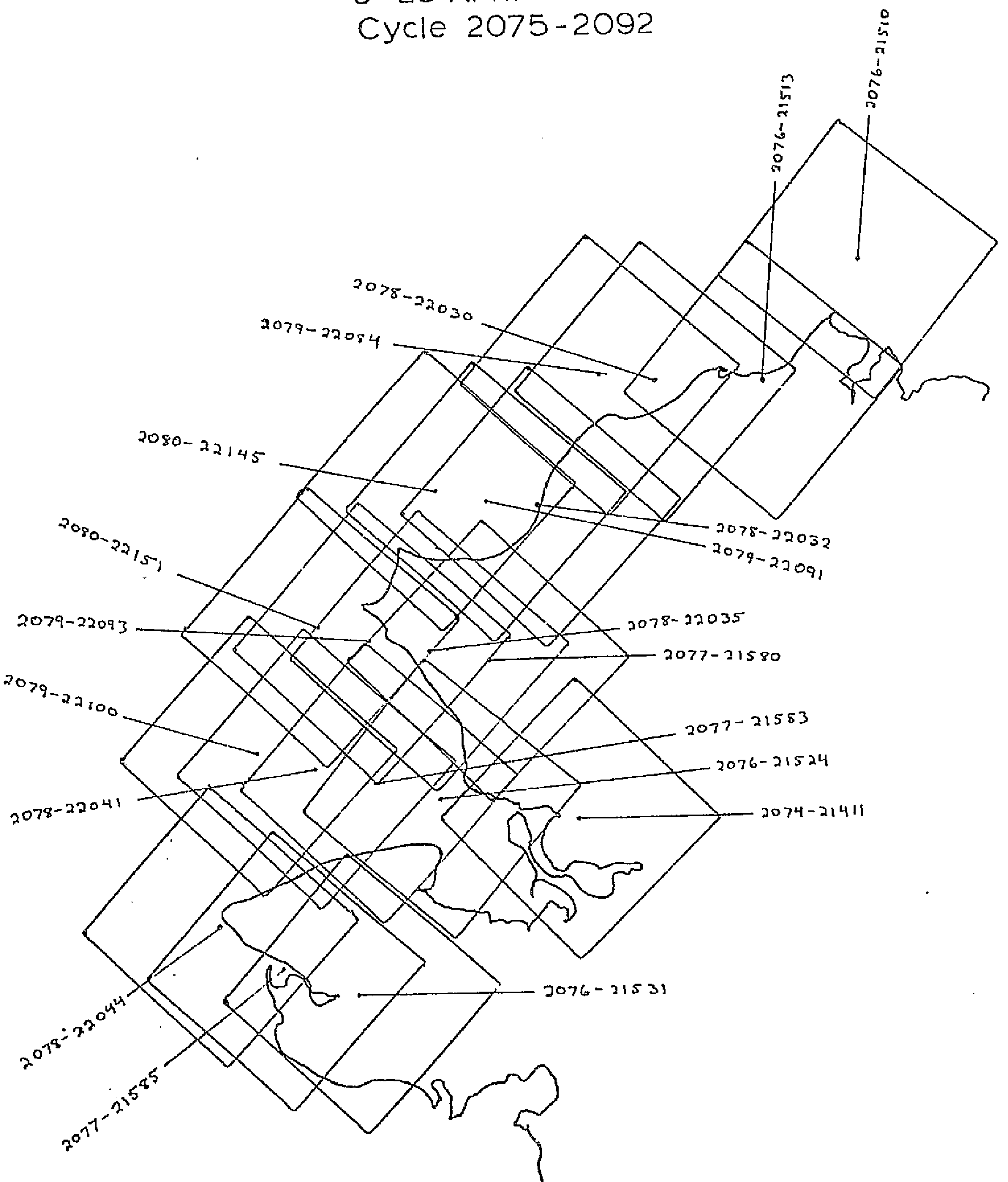
CHUKCHI SEA

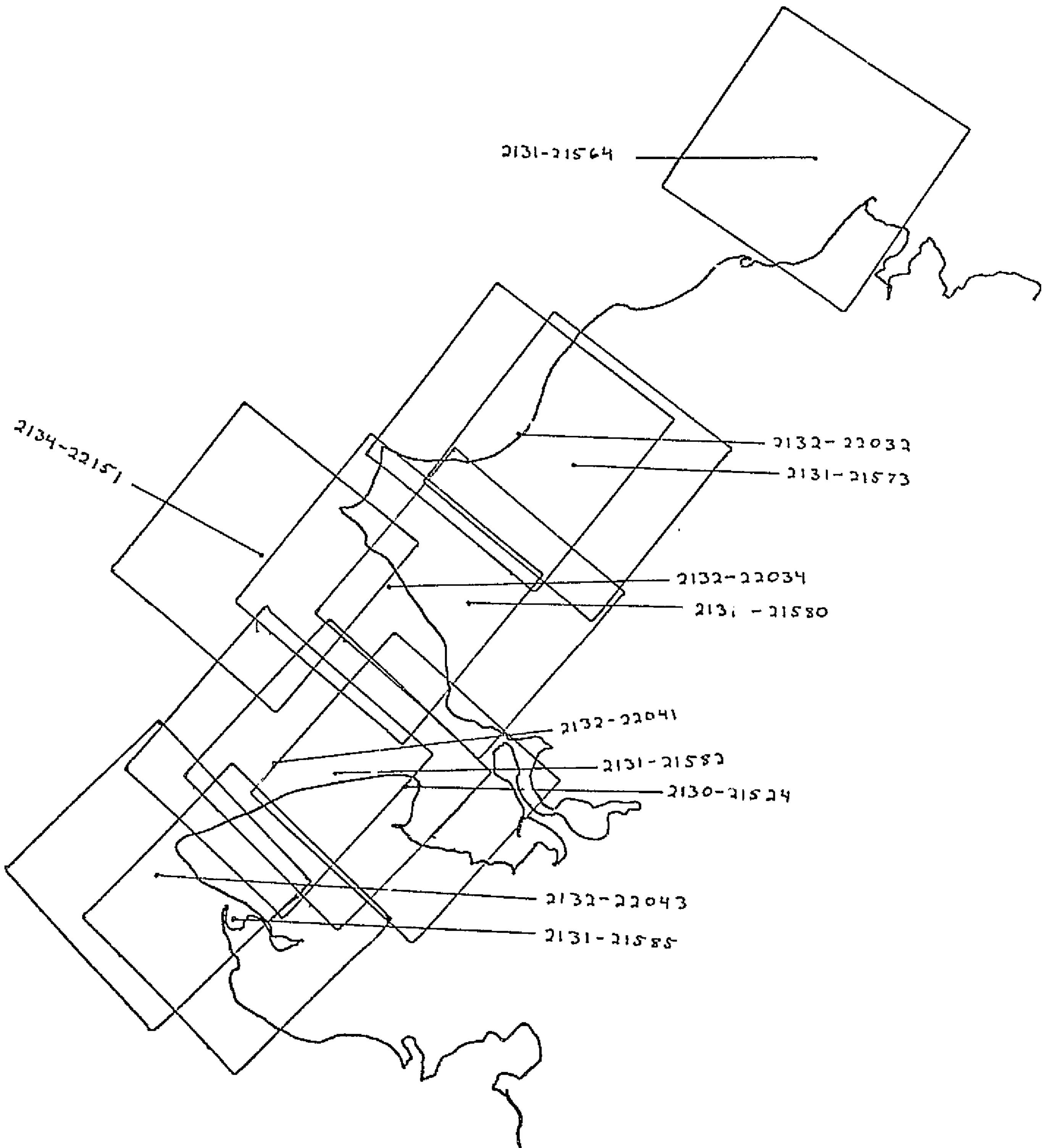
6-23 APRIL 1975
Cycle 2075-2092



II-44 CHUKCHI SEA

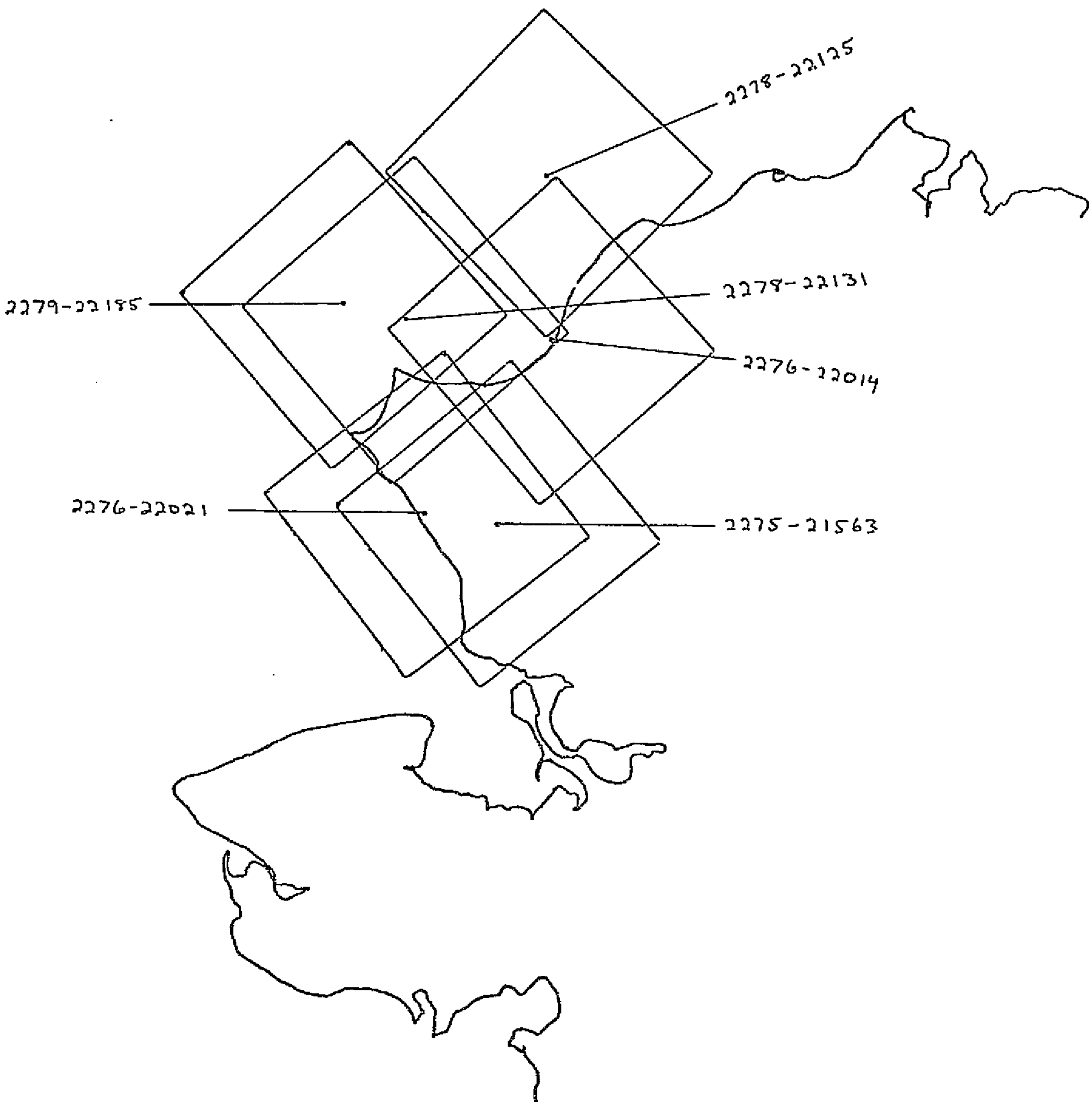
30 MAY-16 JUNE 1975

Cycle 2128-2145



II-45 CHUKCHI SEA

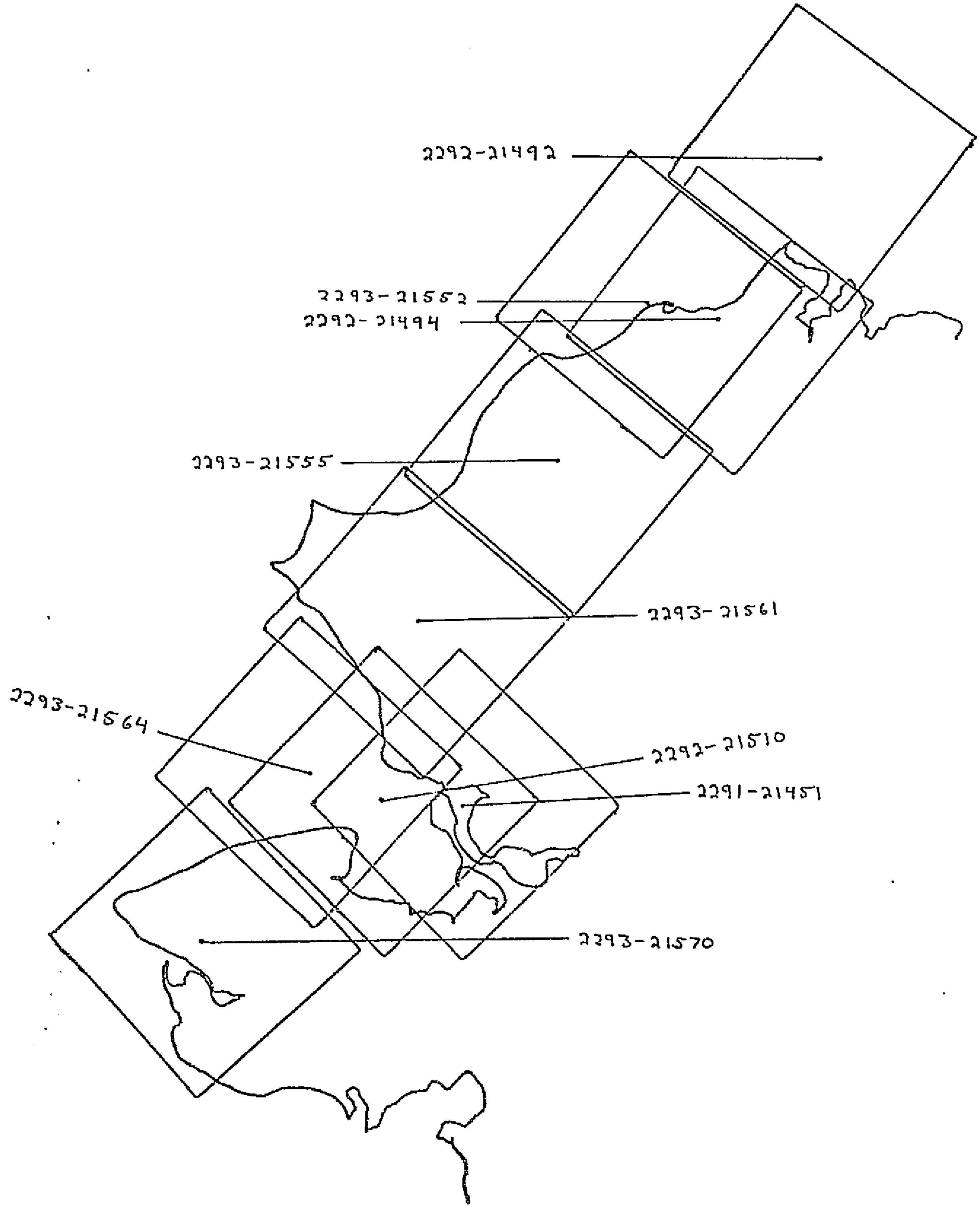
21 OCTOBER-8 NOVEMBER 1975
Cycle 2272-2290



II-46

CHUKCHI SEA

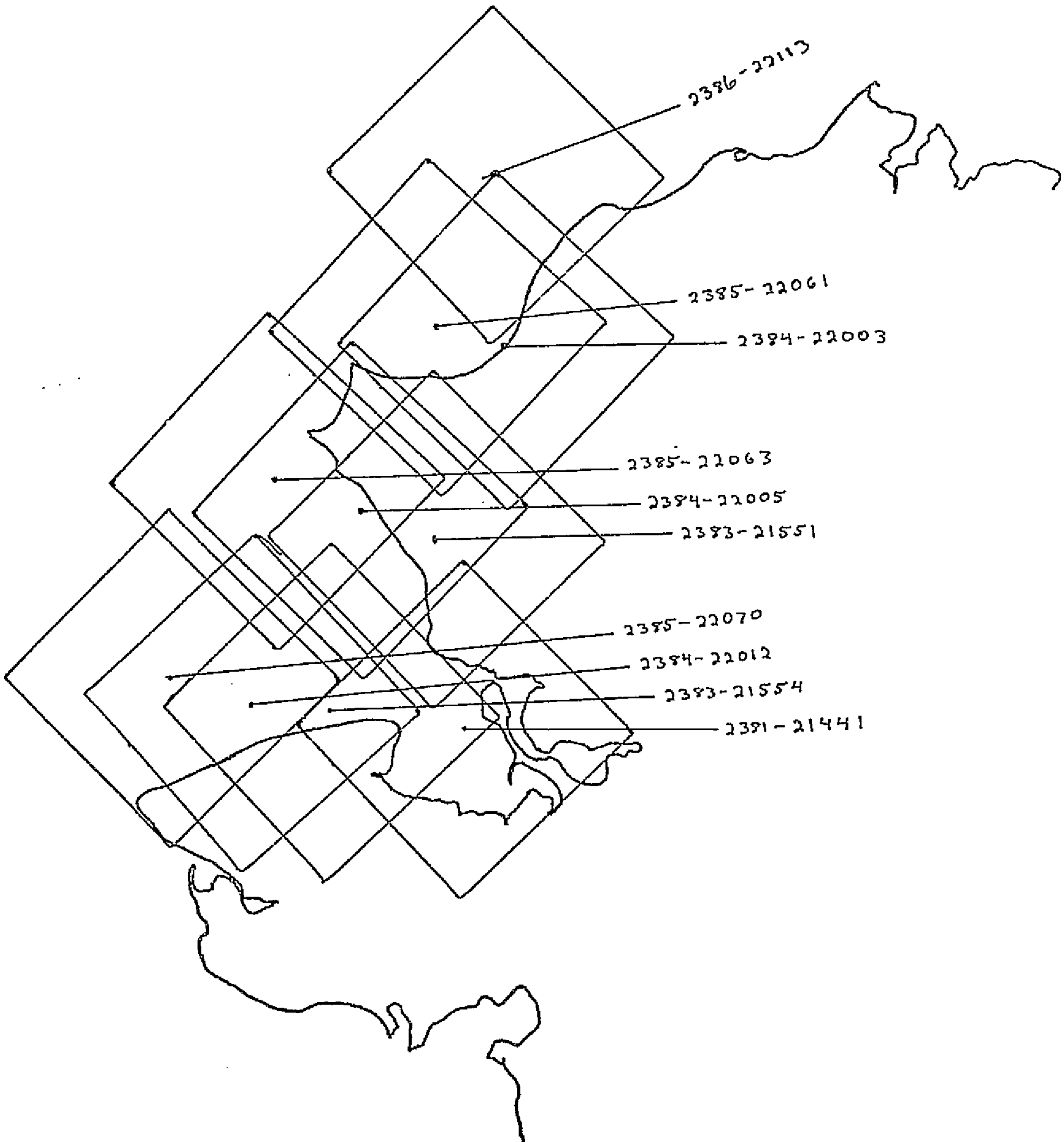
9-26 NOVEMBER 1975
Cycle 2291-2308



II-47

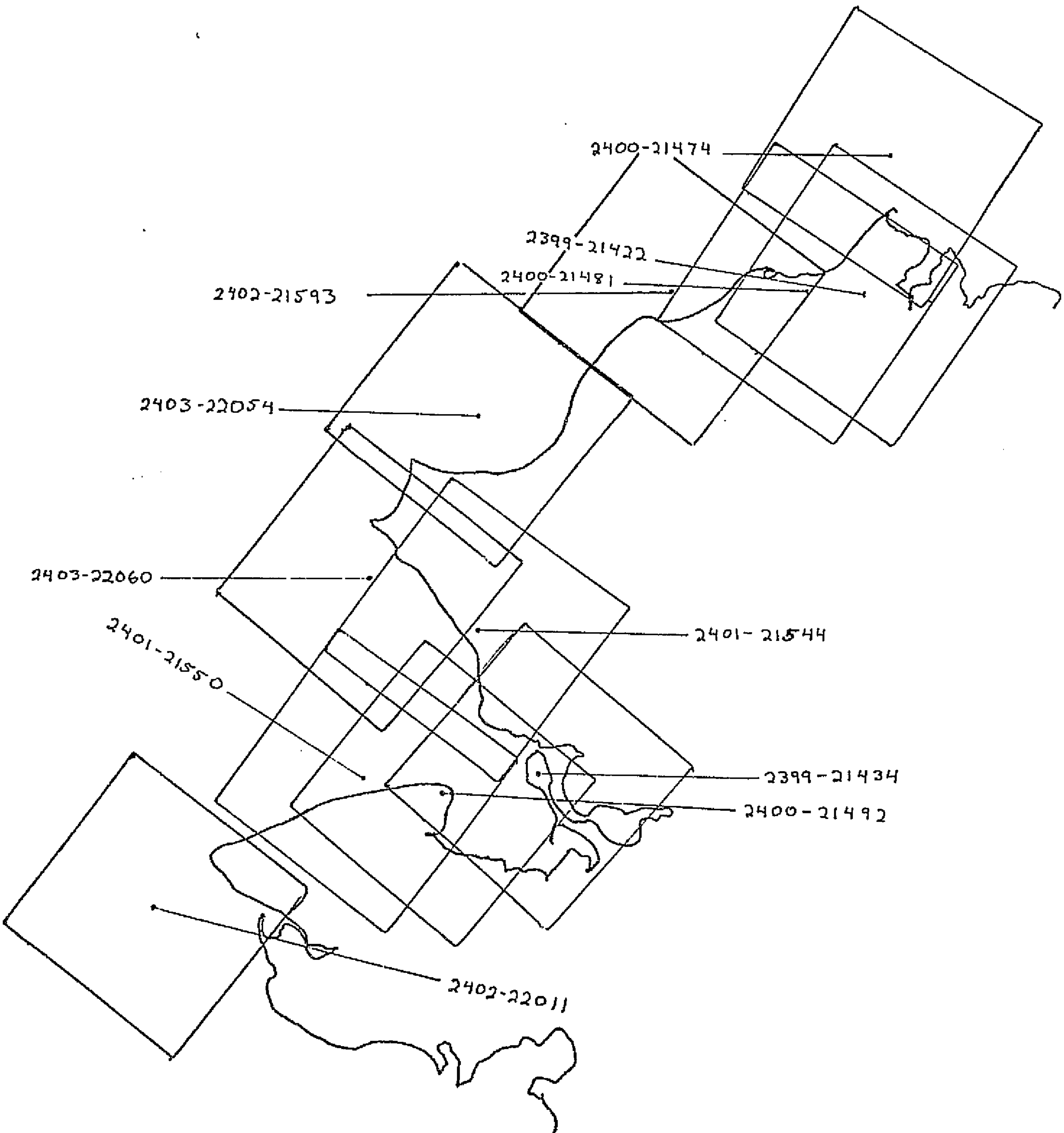
CHUKCHI SEA

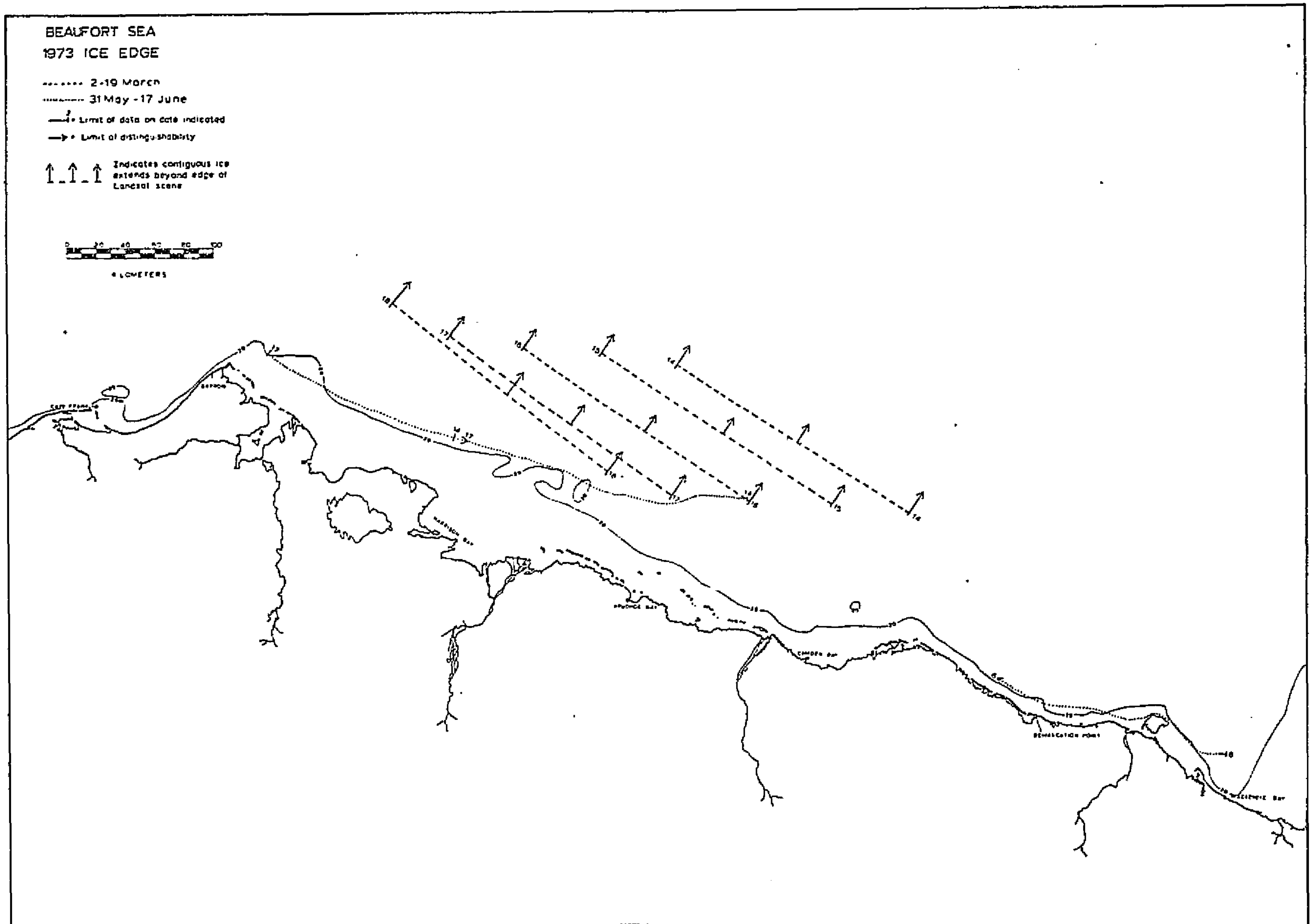
6-23 FEBRUARY 1976
Cycle 2381-2398



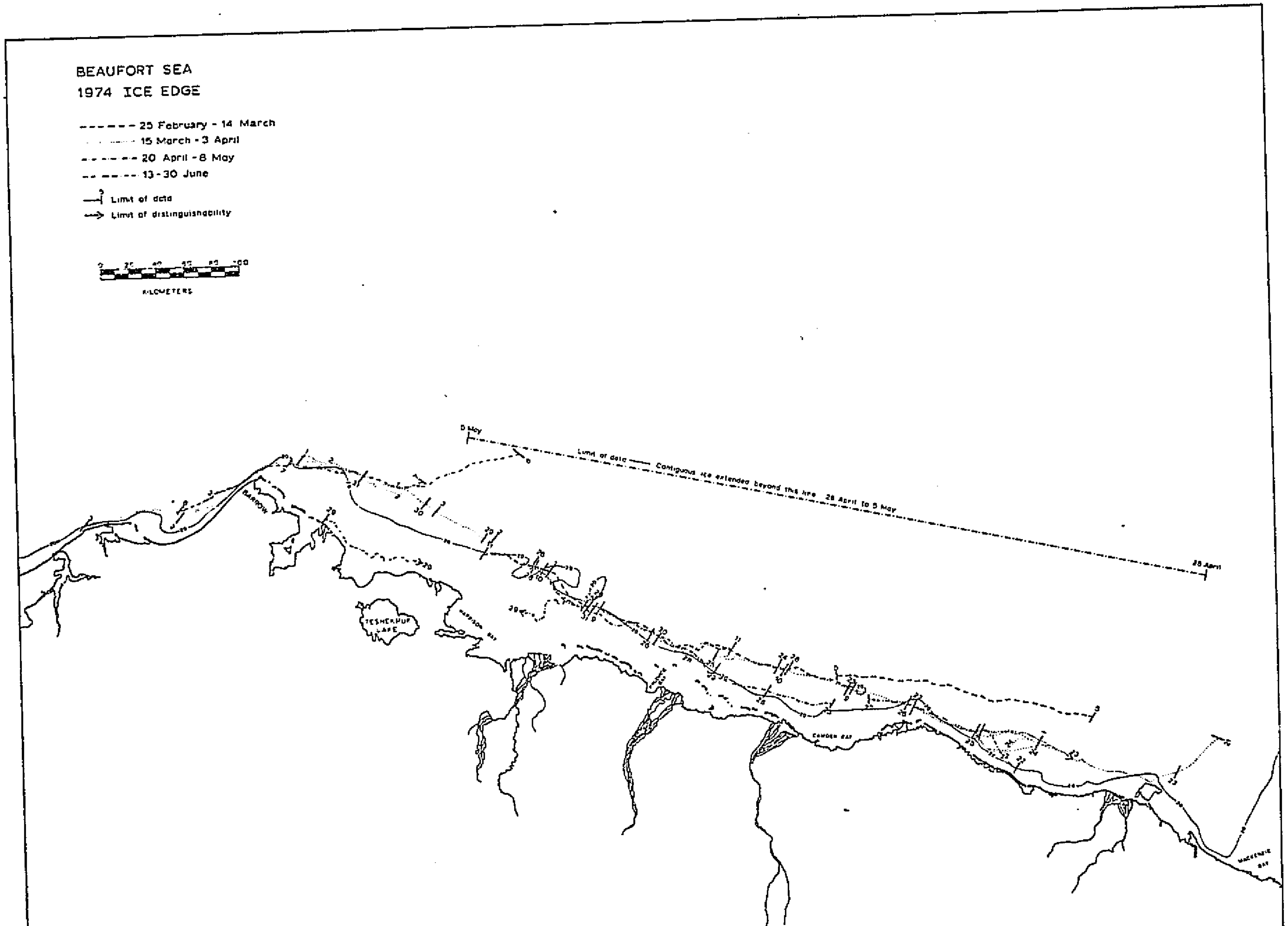
CHUKCHI SEA

24 FEBRUARY - 12 MARCH 1976
Cycle 2399 - 2416

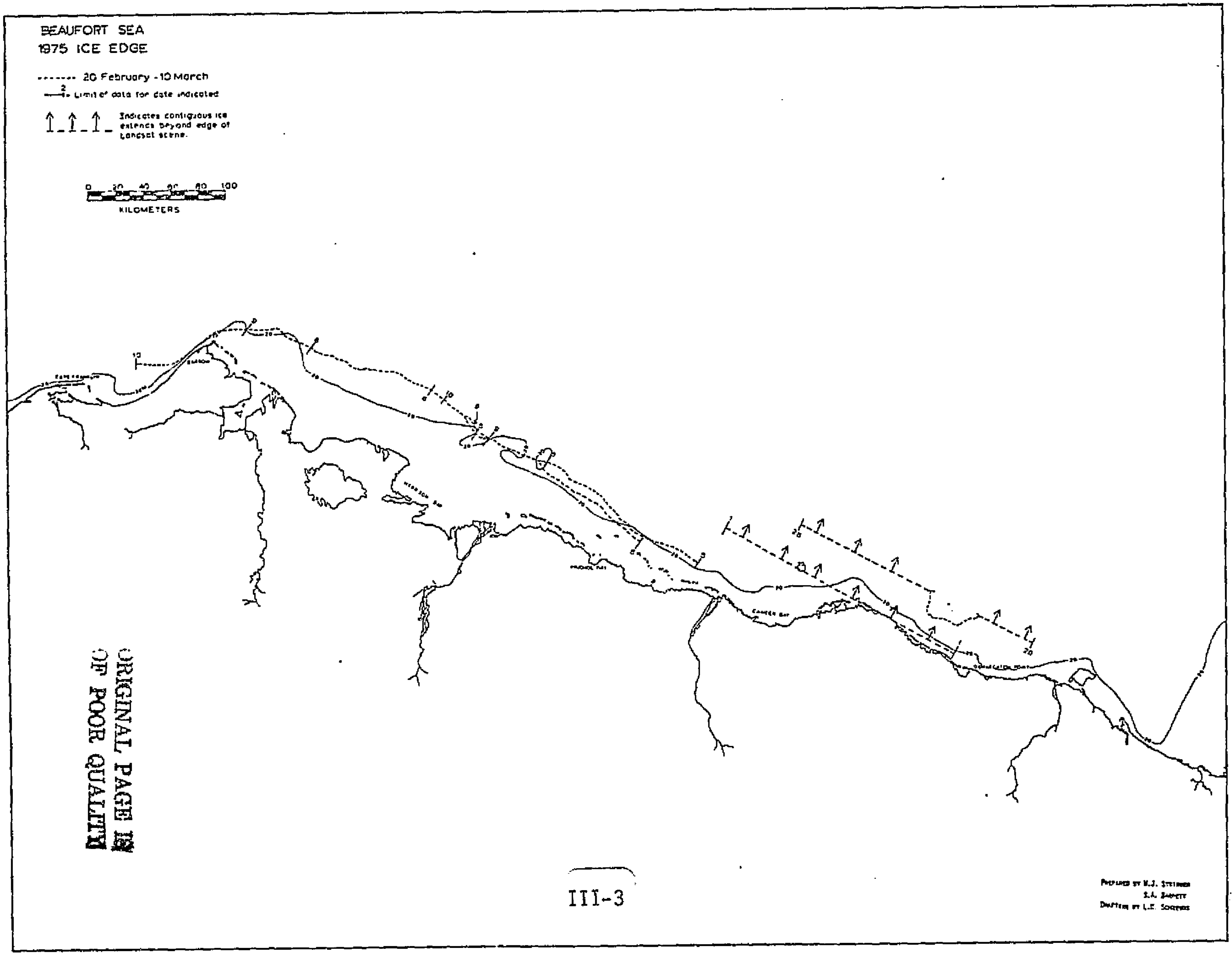


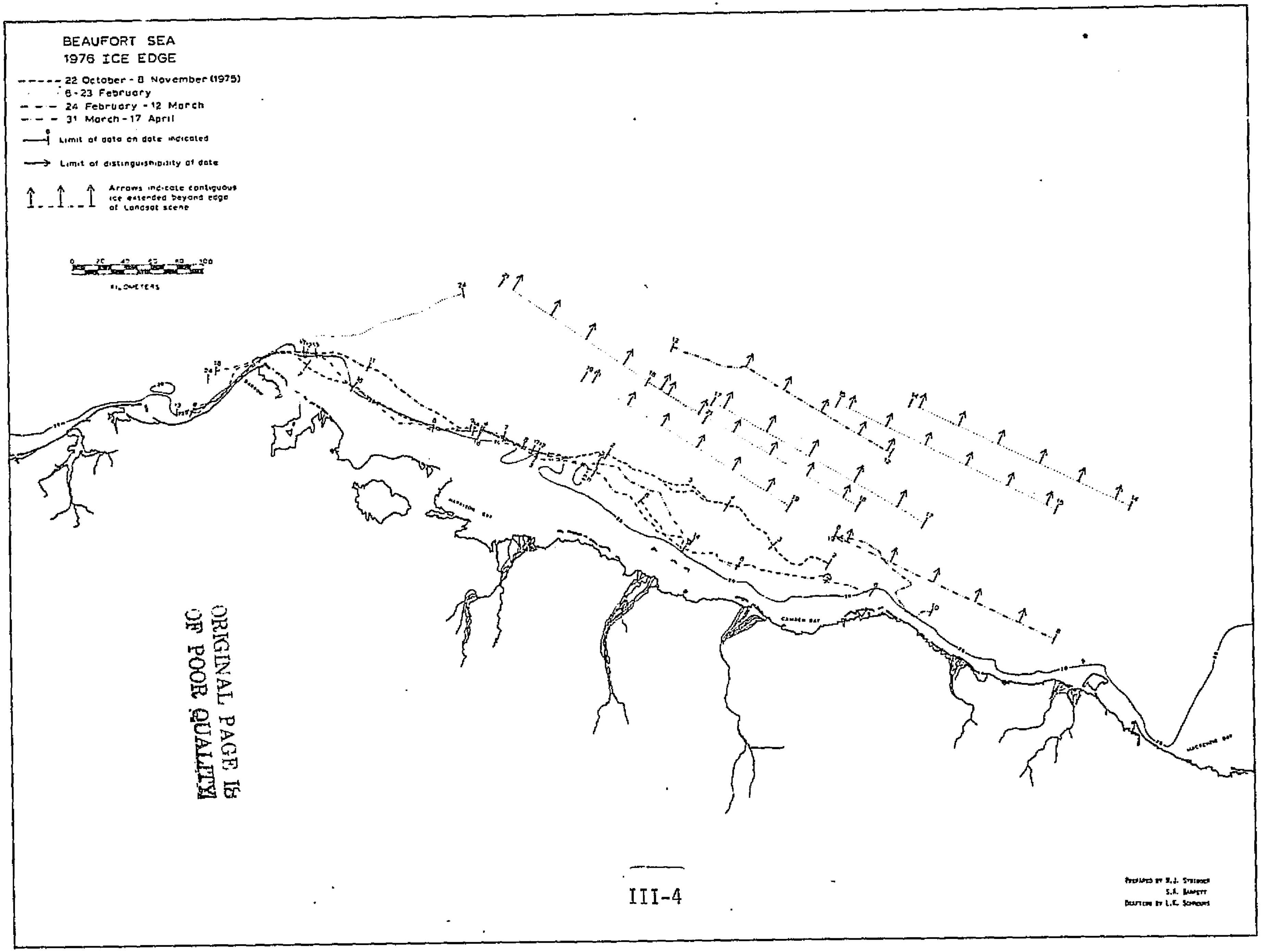

BEAUFORT SEA
1973 ICE EDGE
2-19 March
31 May - 17 June
Limit of data on date indicated
Limit of distinguishability
Indicates contiguous ice extends beyond edge of Landsat scene
KILOMETERS

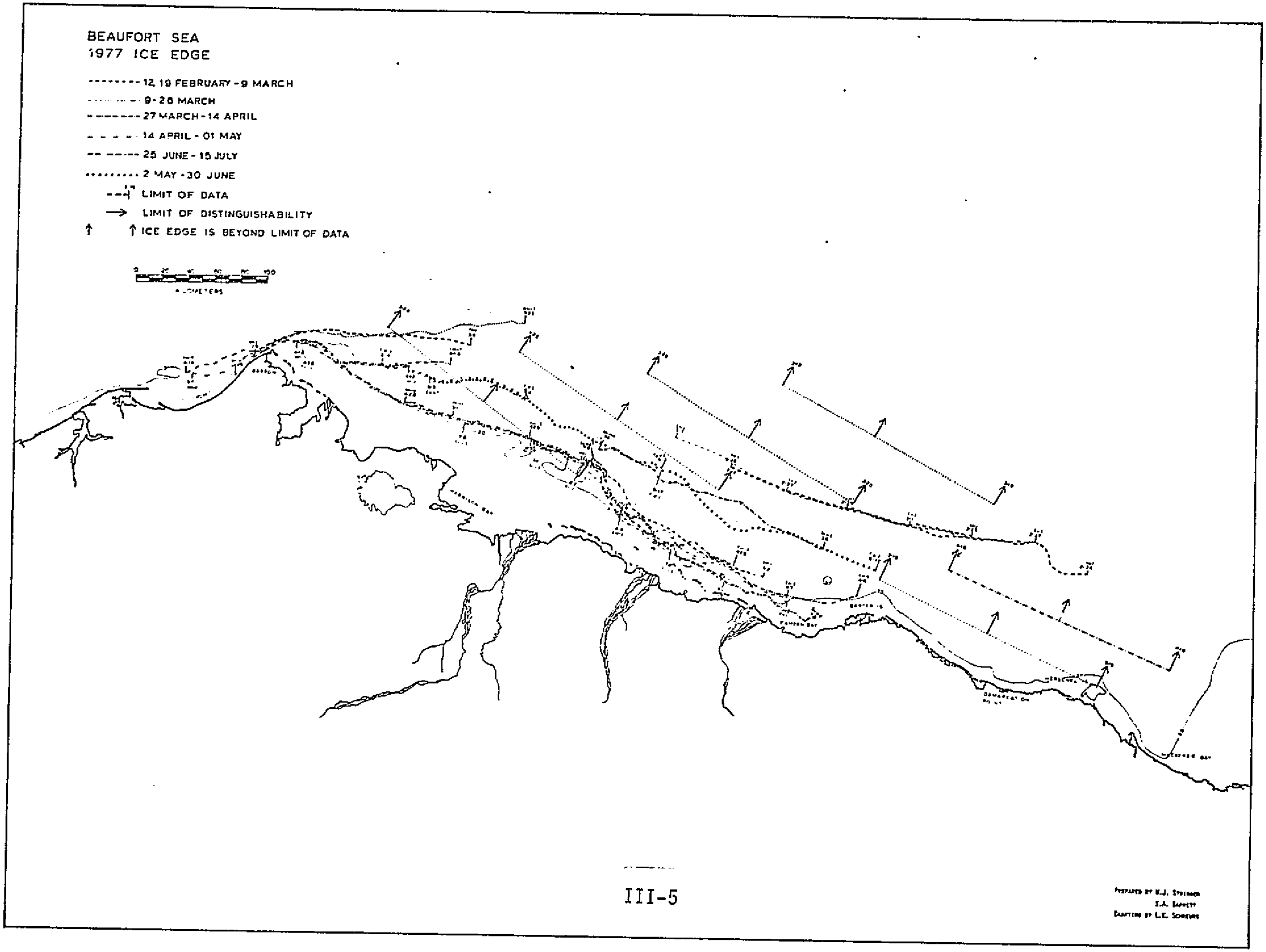
III-1



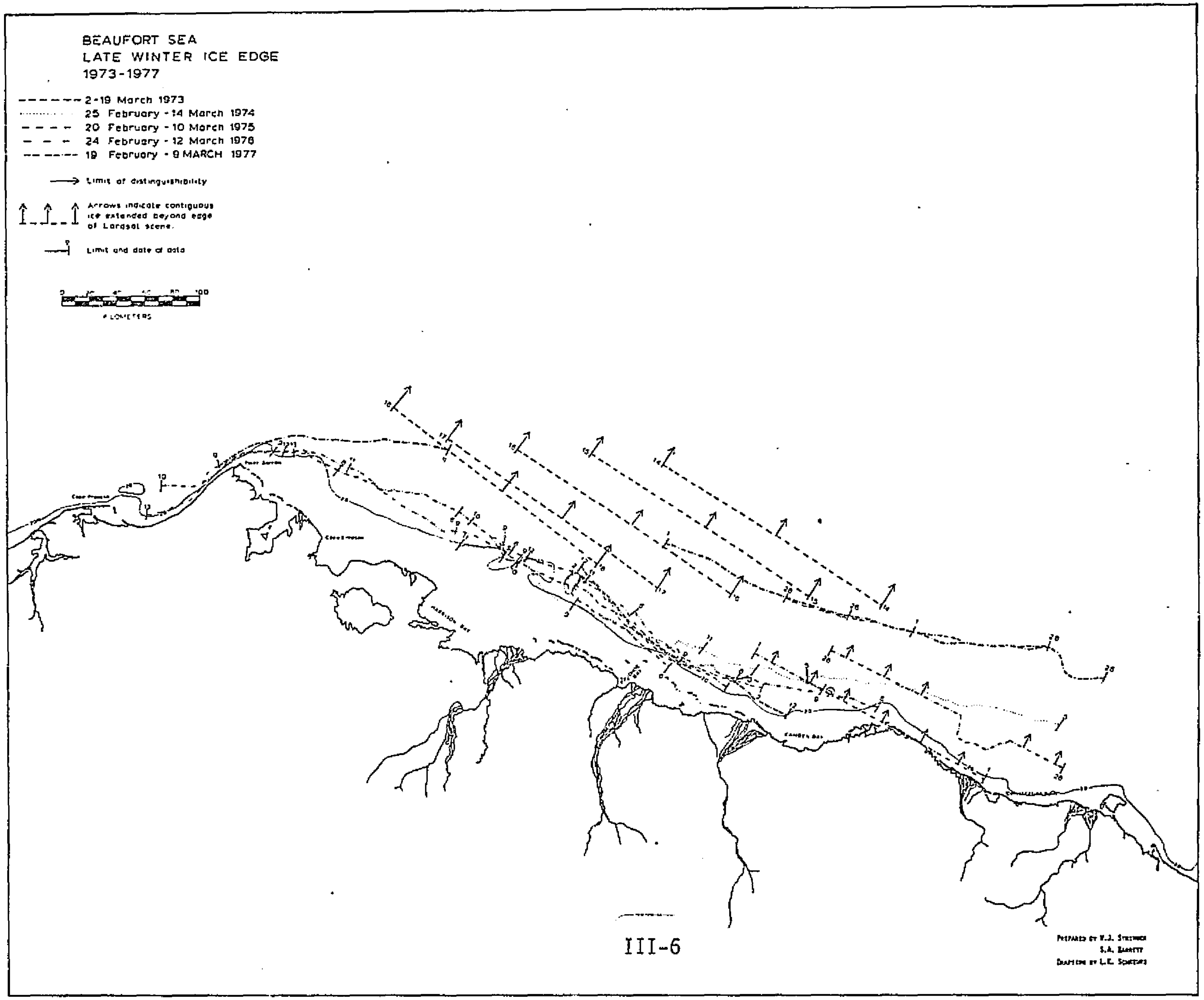
BEAUFORT SEA
1974 ICE EDGE
25 February - 14 March
15 March - 3 April
20 April - 8 May
13 - 30 June
Limit of data
Limit of distinguishability
KILOMETERS
Limit of data
Contiguous ice extended beyond this line 28 April to 5 May
CAMDEN BAY
TESHEKPUK LAKE

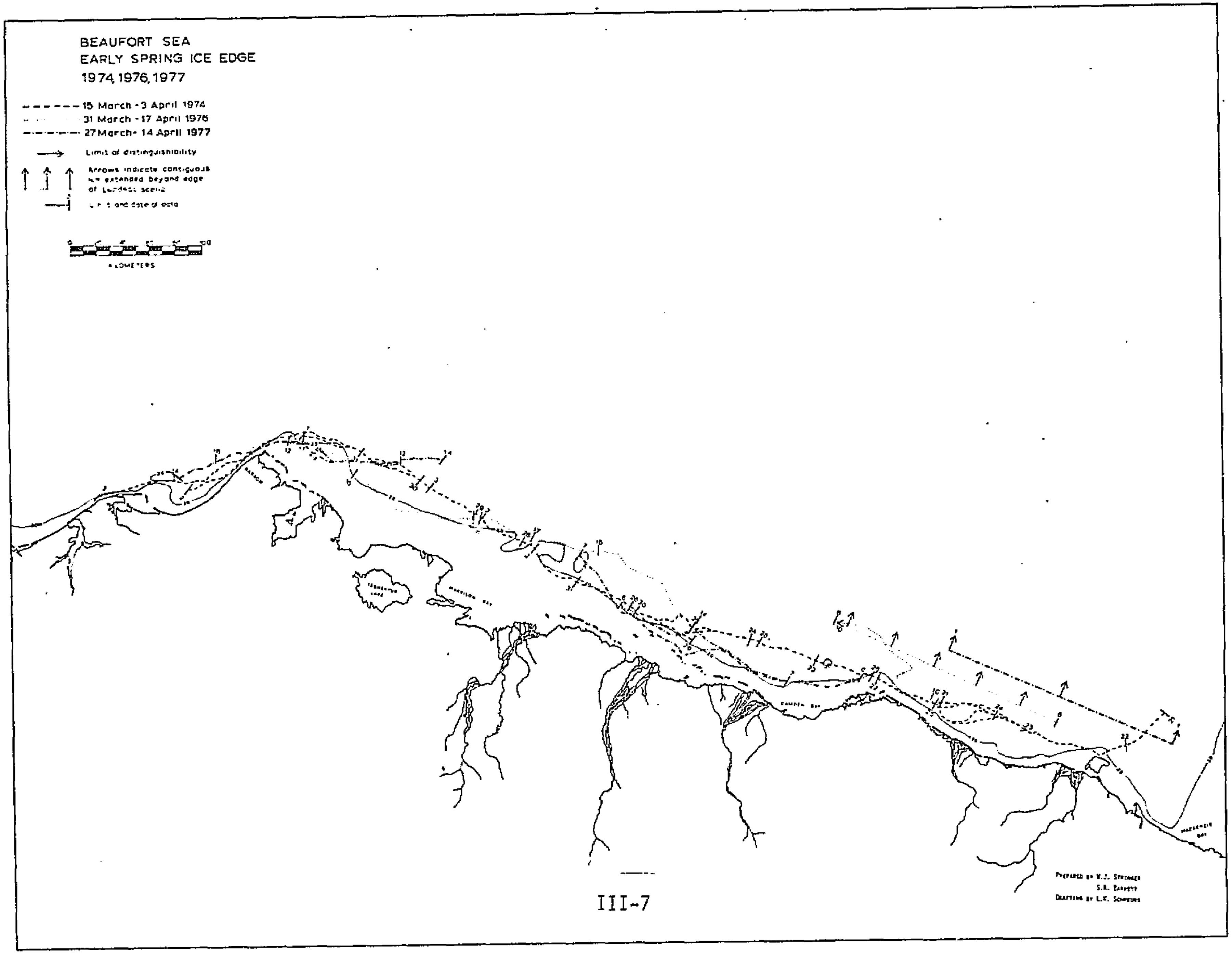

BEAUFORT SEA
1975 ICE EDGE
20 February - 10 March
Limit of data for date indicated
Indicates contiguous ice extends beyond edge of Landsat scene.
0 20 40 60 80 100
KILOMETERS

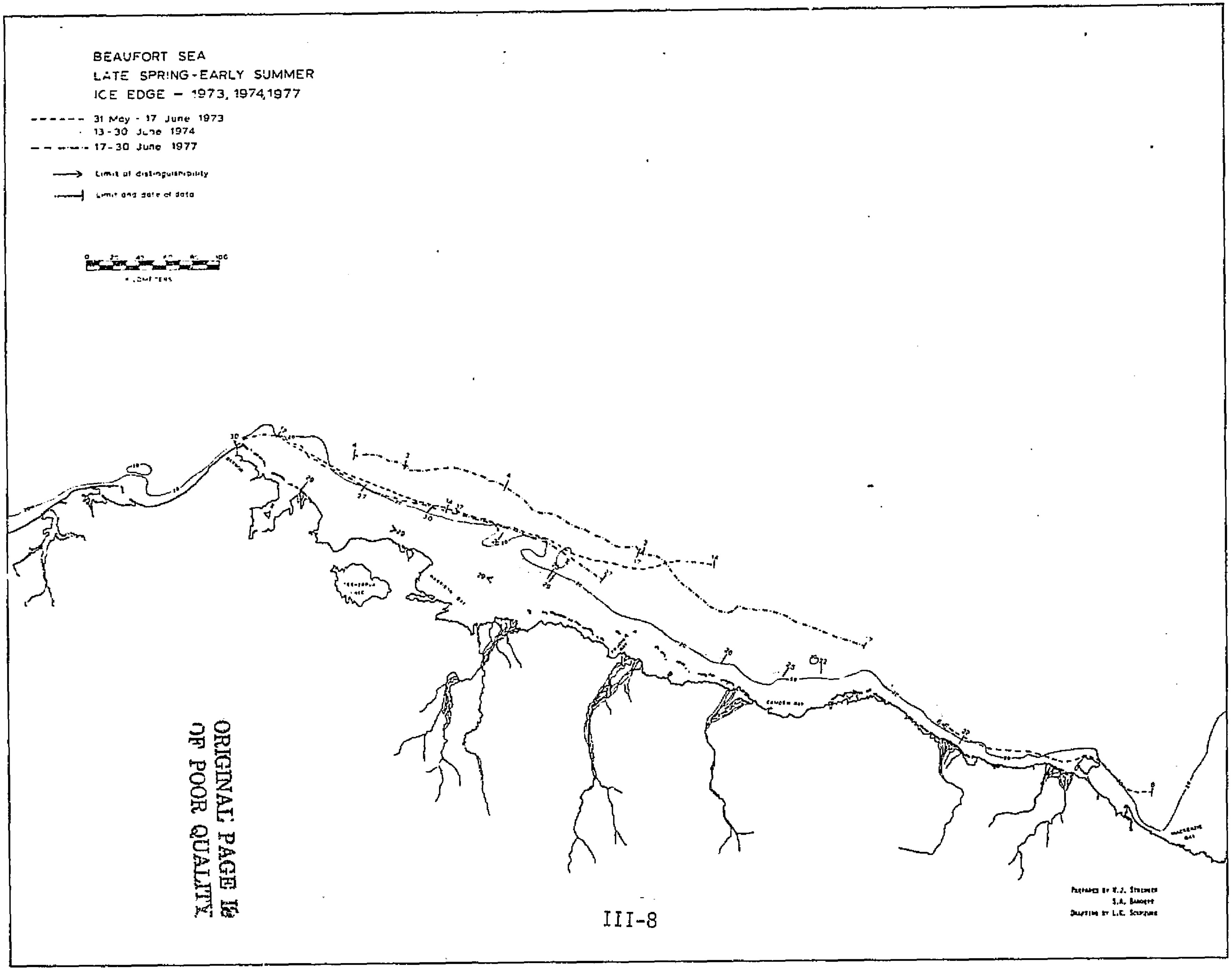

BEAUFORT SEA
1976 ICE EDGE
22 October - 8 November (1975)
6-23 February
24 February - 12 March
31 March - 17 April
Limit of data on date indicated
Limit of distinguishability of data
Arrows indicate contiguous ice extended beyond edge of Landsat scene
KILOMETERS
CAMDEN BAY


BEAUFORT SEA
1977 ICE EDGE
12, 19 FEBRUARY - 9 MARCH
9 - 28 MARCH
27 MARCH - 14 APRIL
14 APRIL - 01 MAY
25 JUNE - 15 JULY
2 MAY - 30 JUNE
LIMIT OF DATA
LIMIT OF DISTINGUISHABILITY
ICE EDGE IS BEYOND LIMIT OF DATA
KILOMETERS

III-5


BEAUFORT SEA
LATE WINTER ICE EDGE
1973-1977
2-19 March 1973
25 February - 14 March 1974
20 February - 10 March 1975
24 February - 12 March 1976
19 February - 9 MARCH 1977
Limit of distinguishability
Arrows indicate contiguous ice extended beyond edge of Landsat scene.
Limit and date of data
0
100


BEAUFORT SEA
EARLY SPRING ICE EDGE
1974, 1976, 1977
15 March - 3 April 1974
31 March - 17 April 1976
27 March - 14 April 1977
Limit of distinguishability
Arrows indicate contiguous
ice extended beyond edge
of Landsat scene
KILOMETERS



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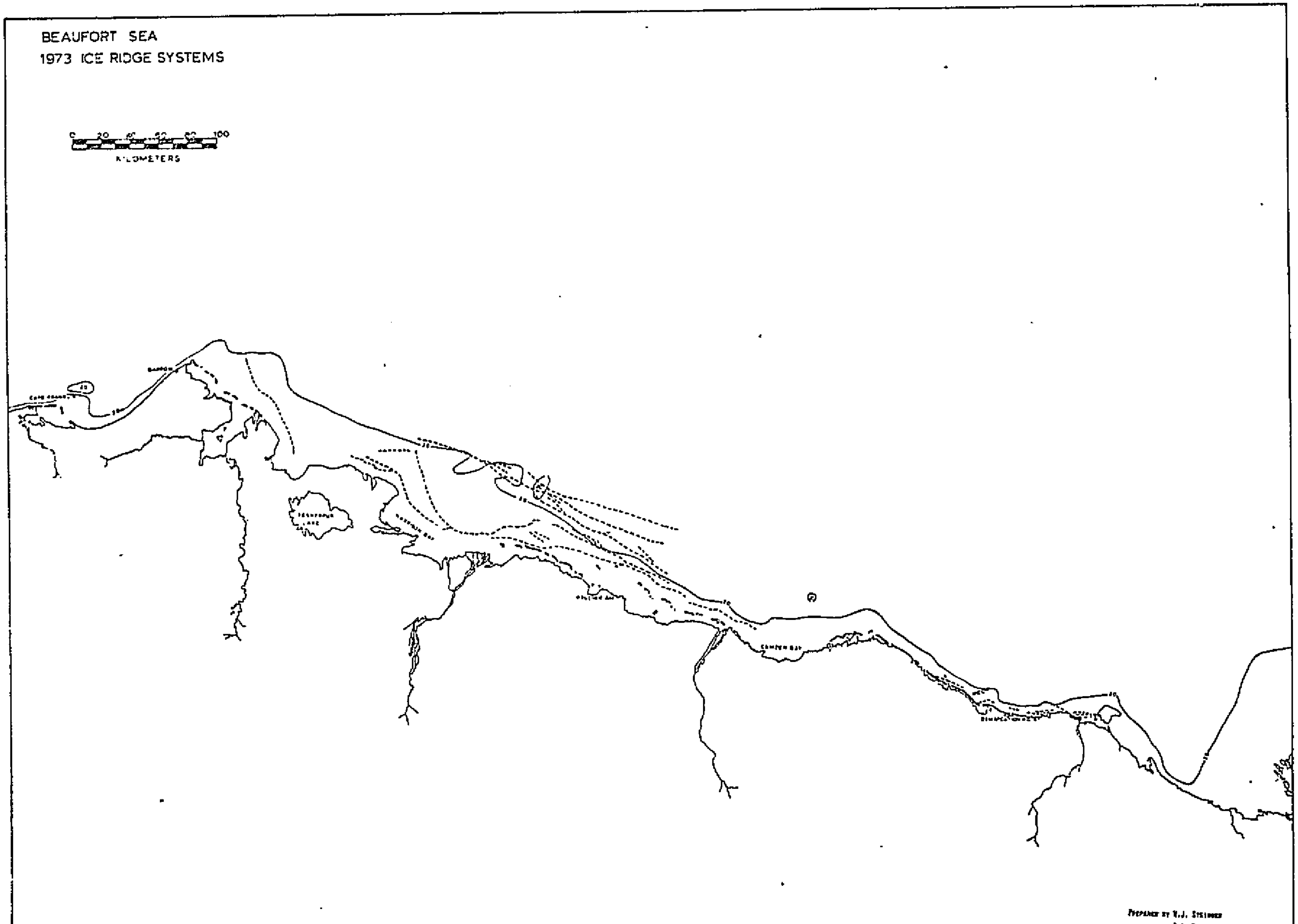
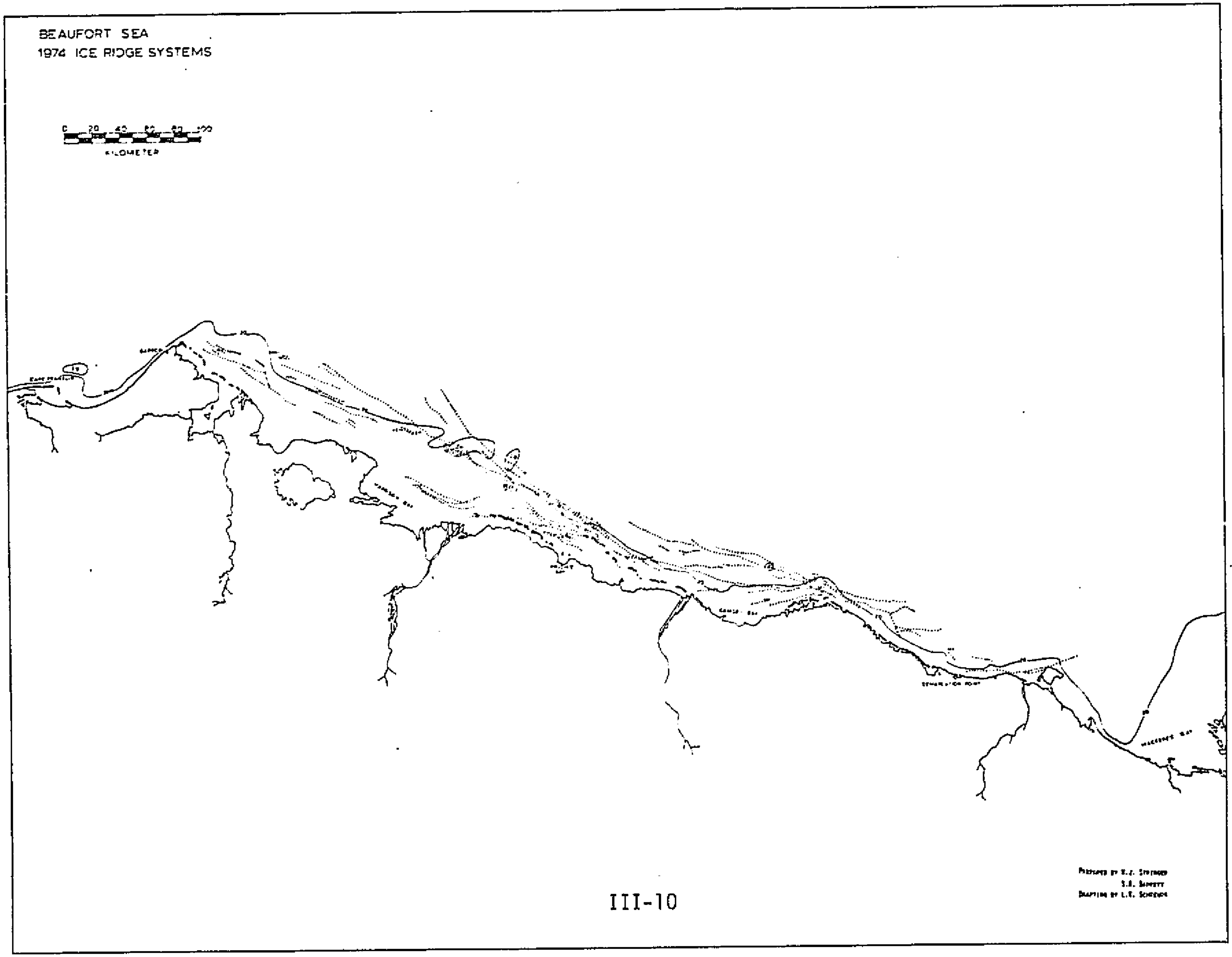
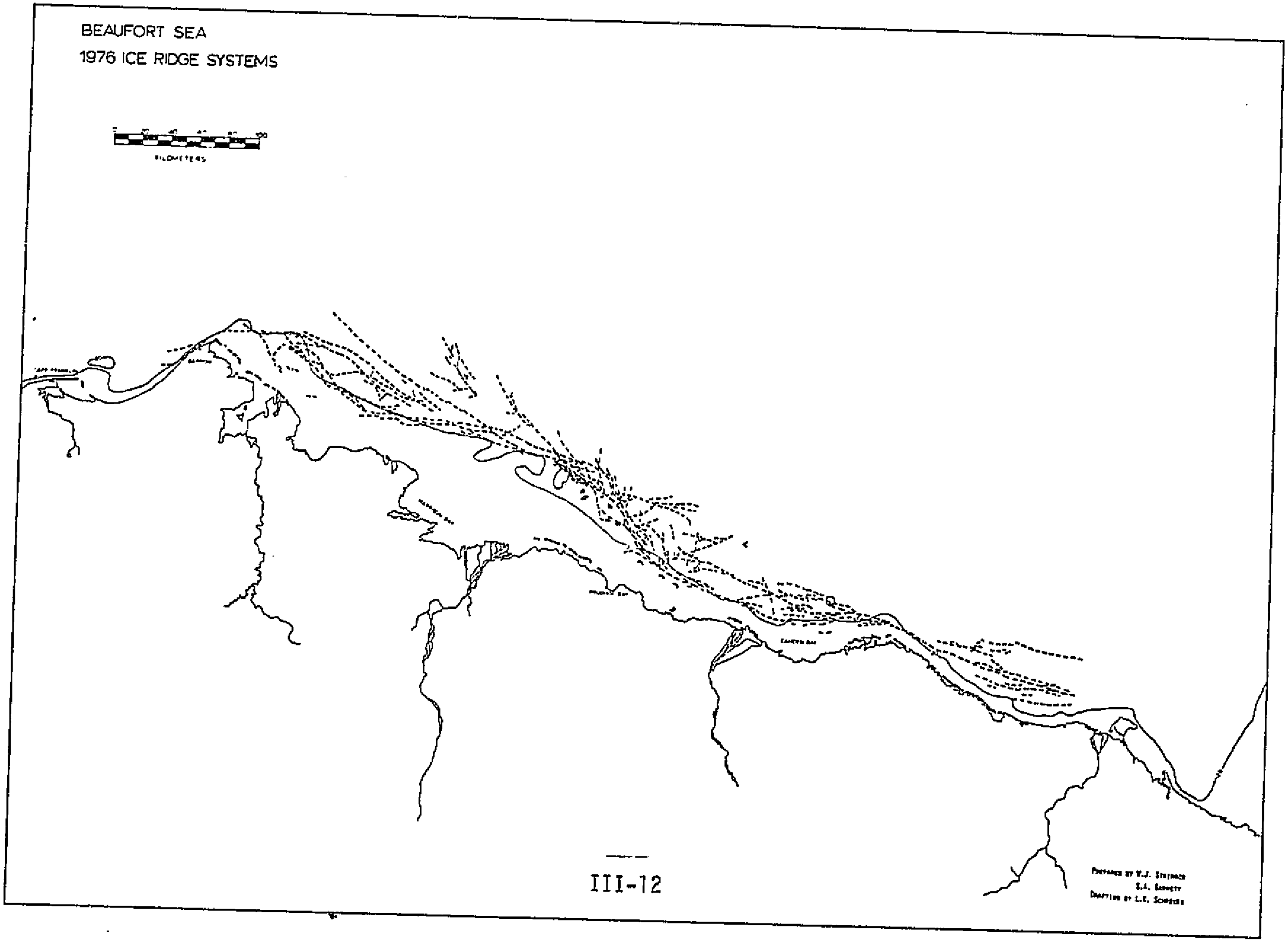

BEAUFORT SEA
1973 ICE RIDGE SYSTEMS
0 20 40 60 80 100
KILOMETERS

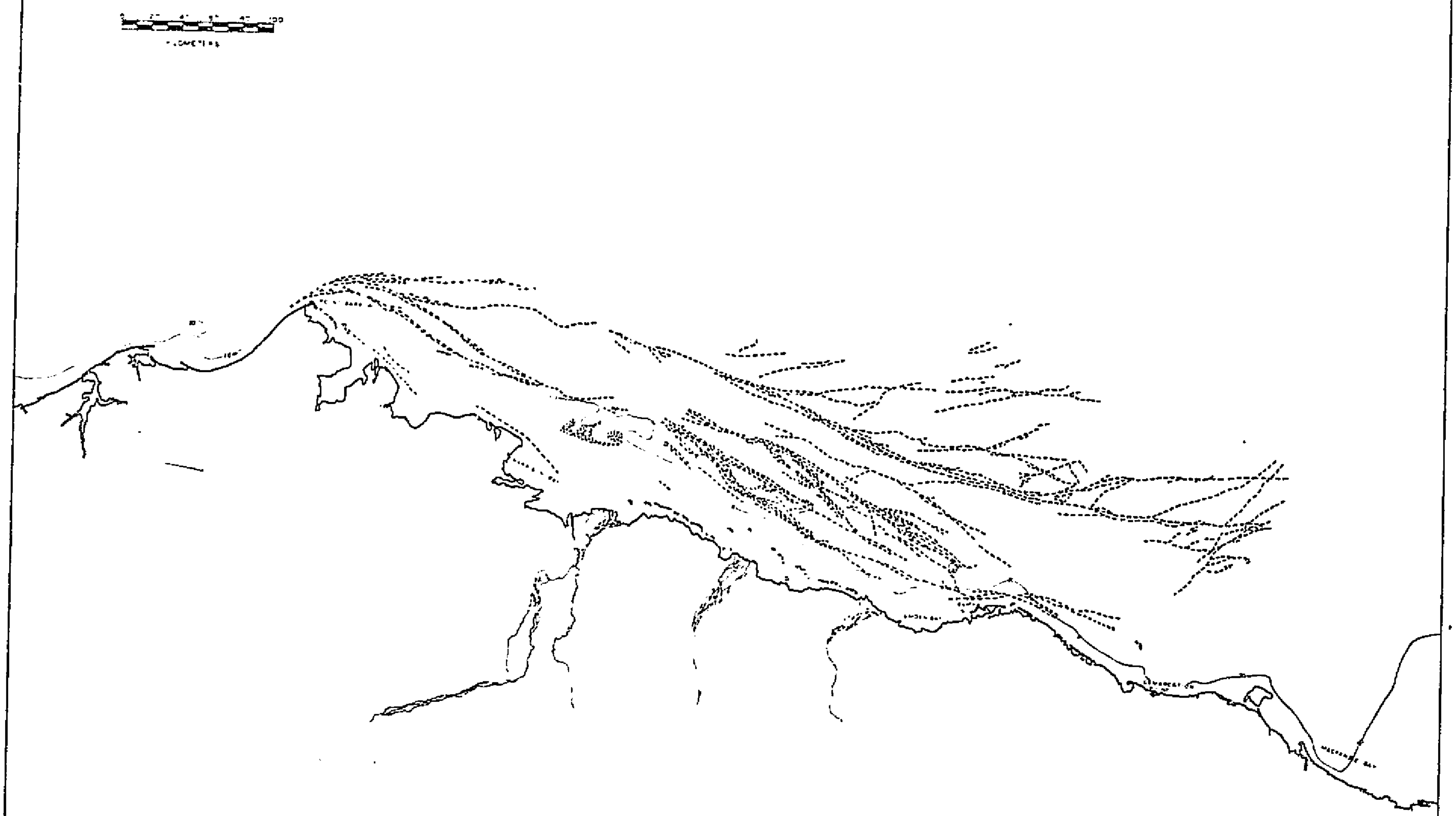

BEAUFORT SEA
1974 ICE RIDGE SYSTEMS
KILOMETER

BEAUFORT SEA
1975 ICE RIDGE SYSTEMS

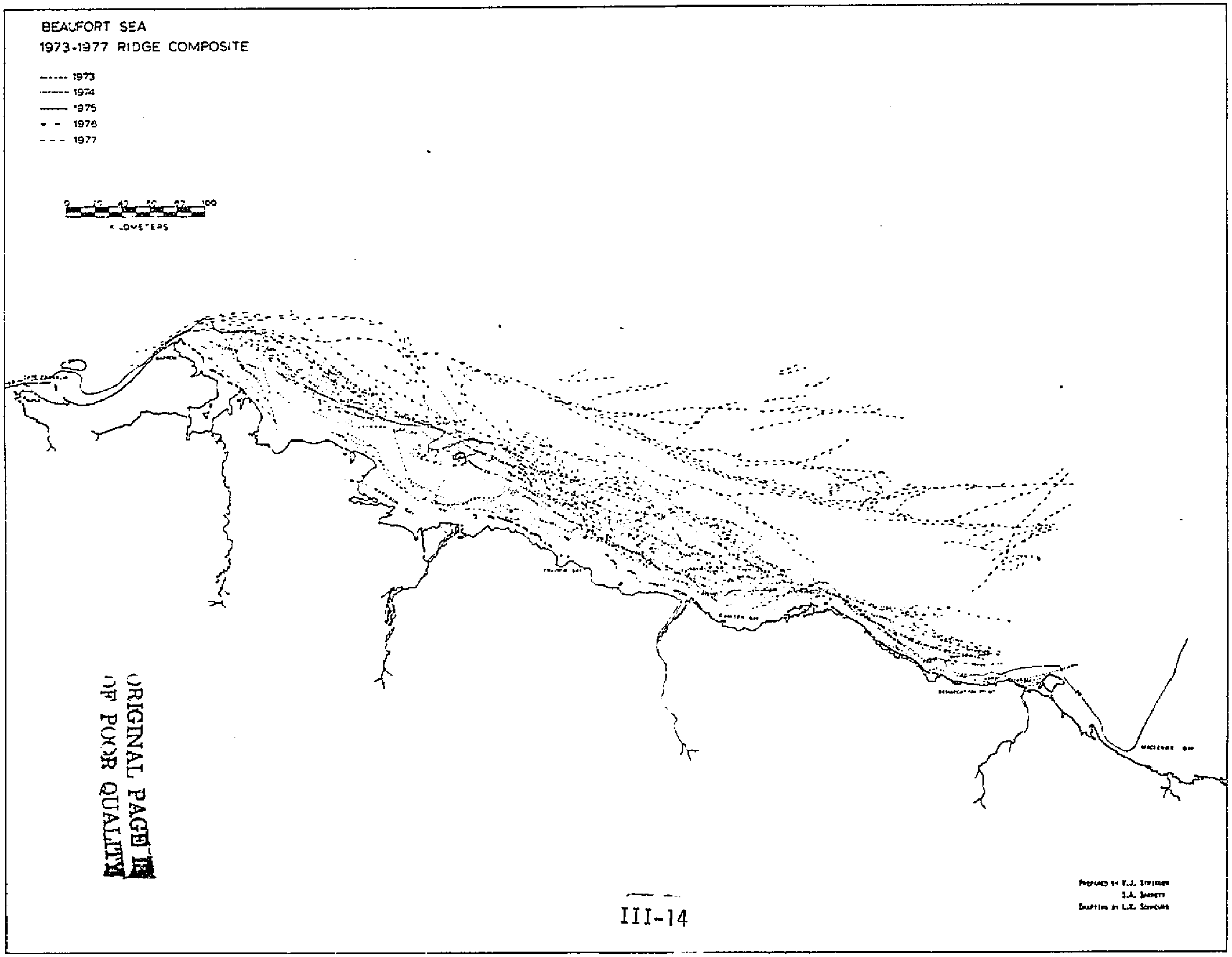
III-11

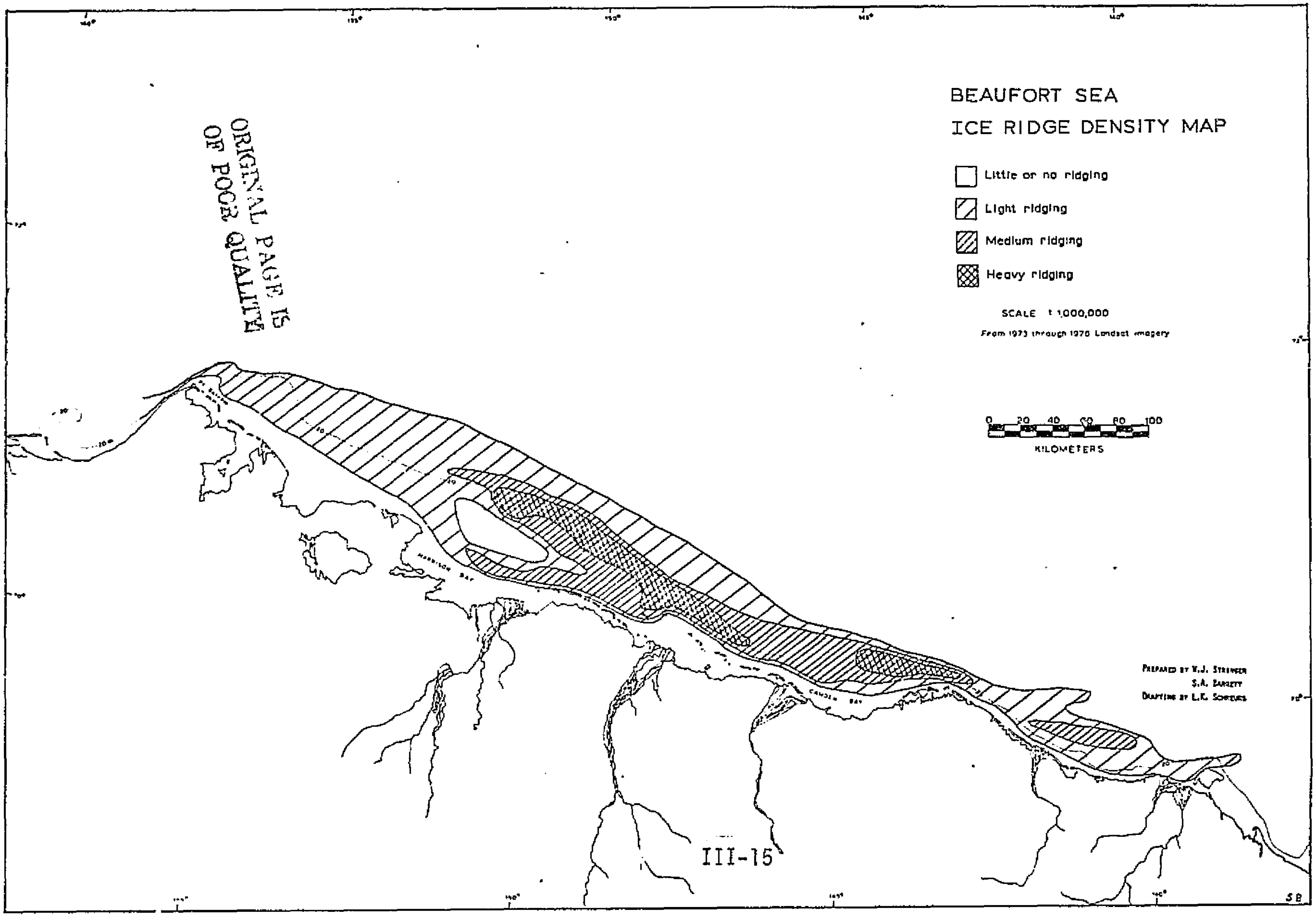

BEAUFORT SEA
1976 ICE RIDGE SYSTEMS
KILOMETERS

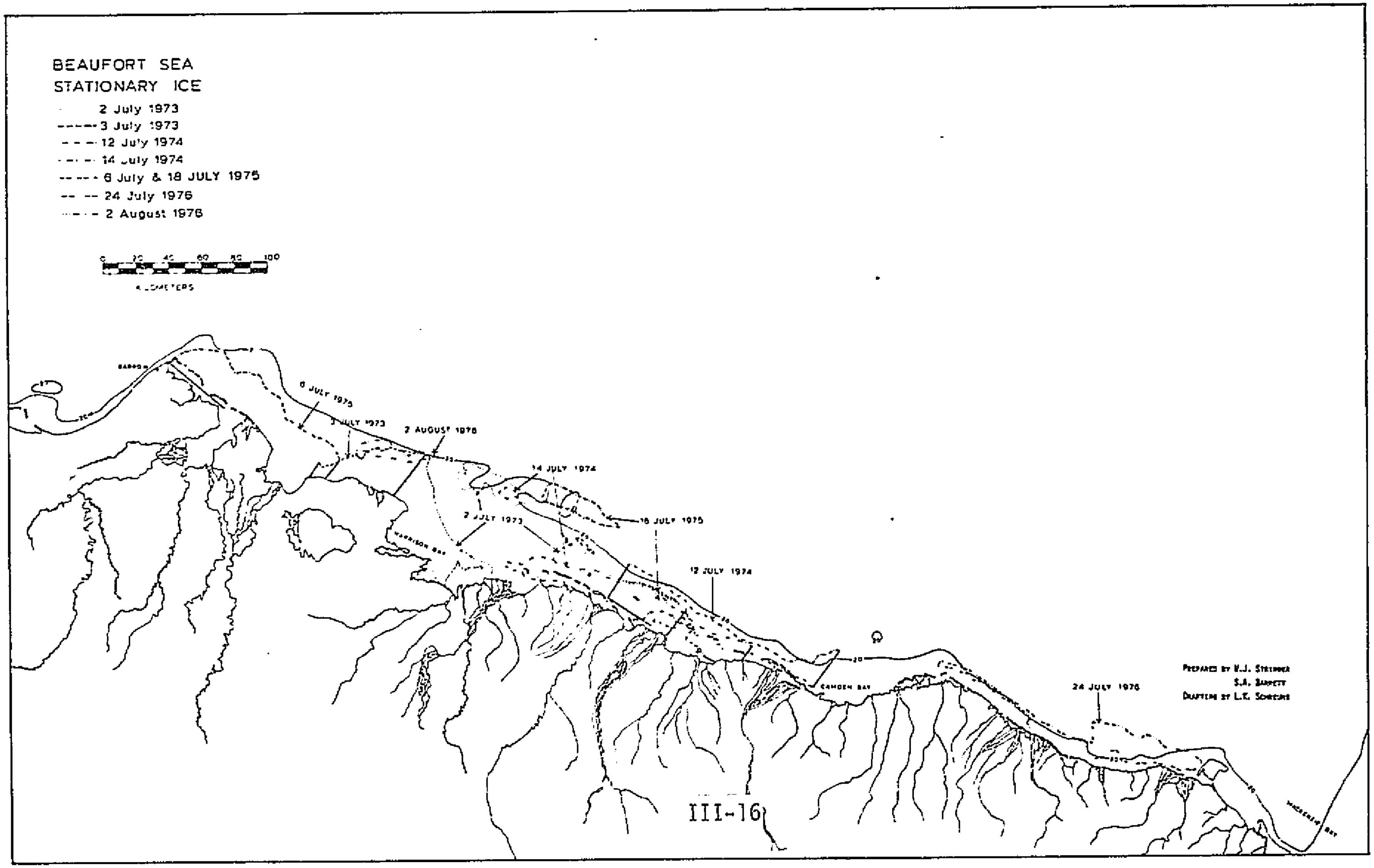
BEAUFORT SEA
1977 ICE RIDGE SYSTEM

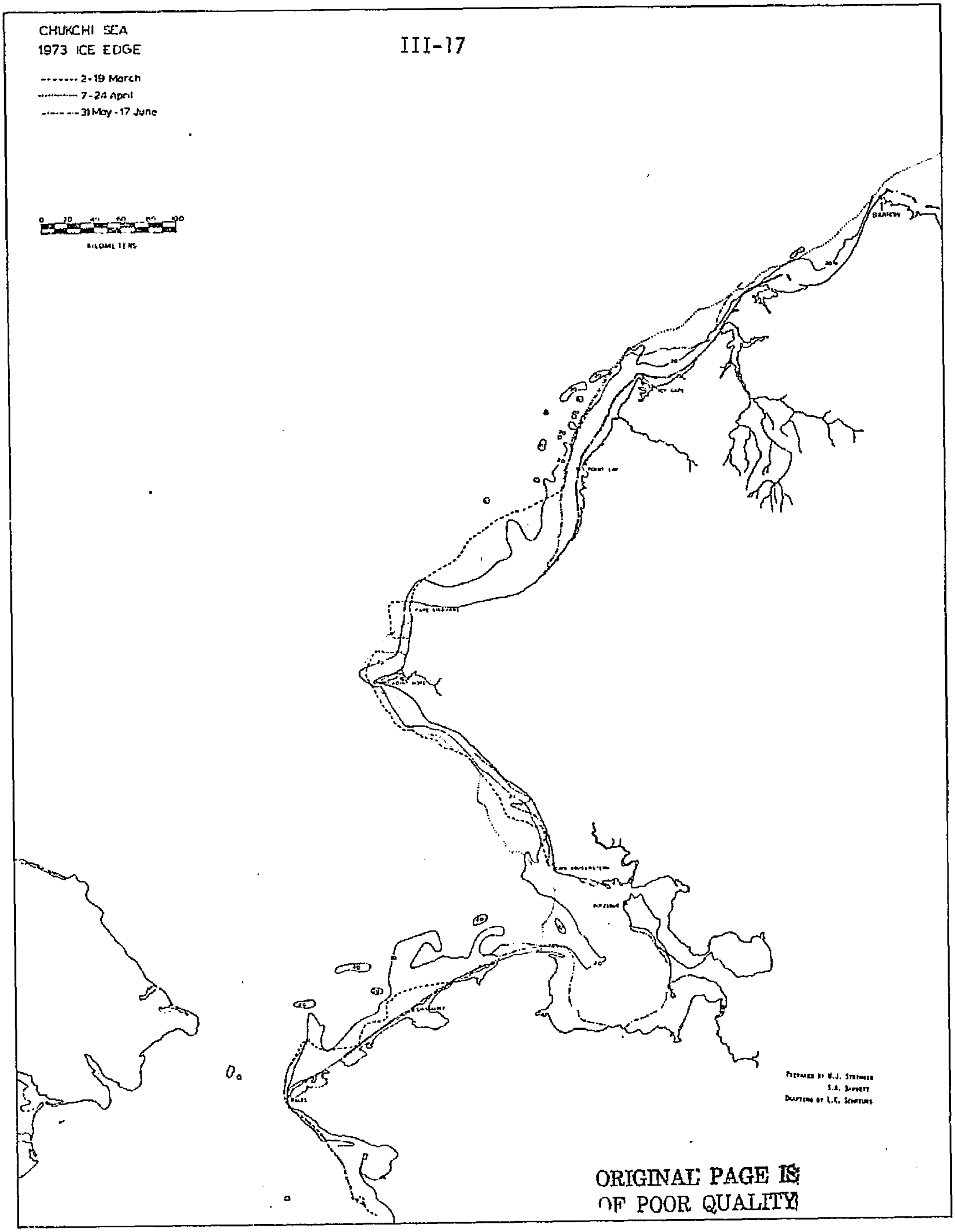


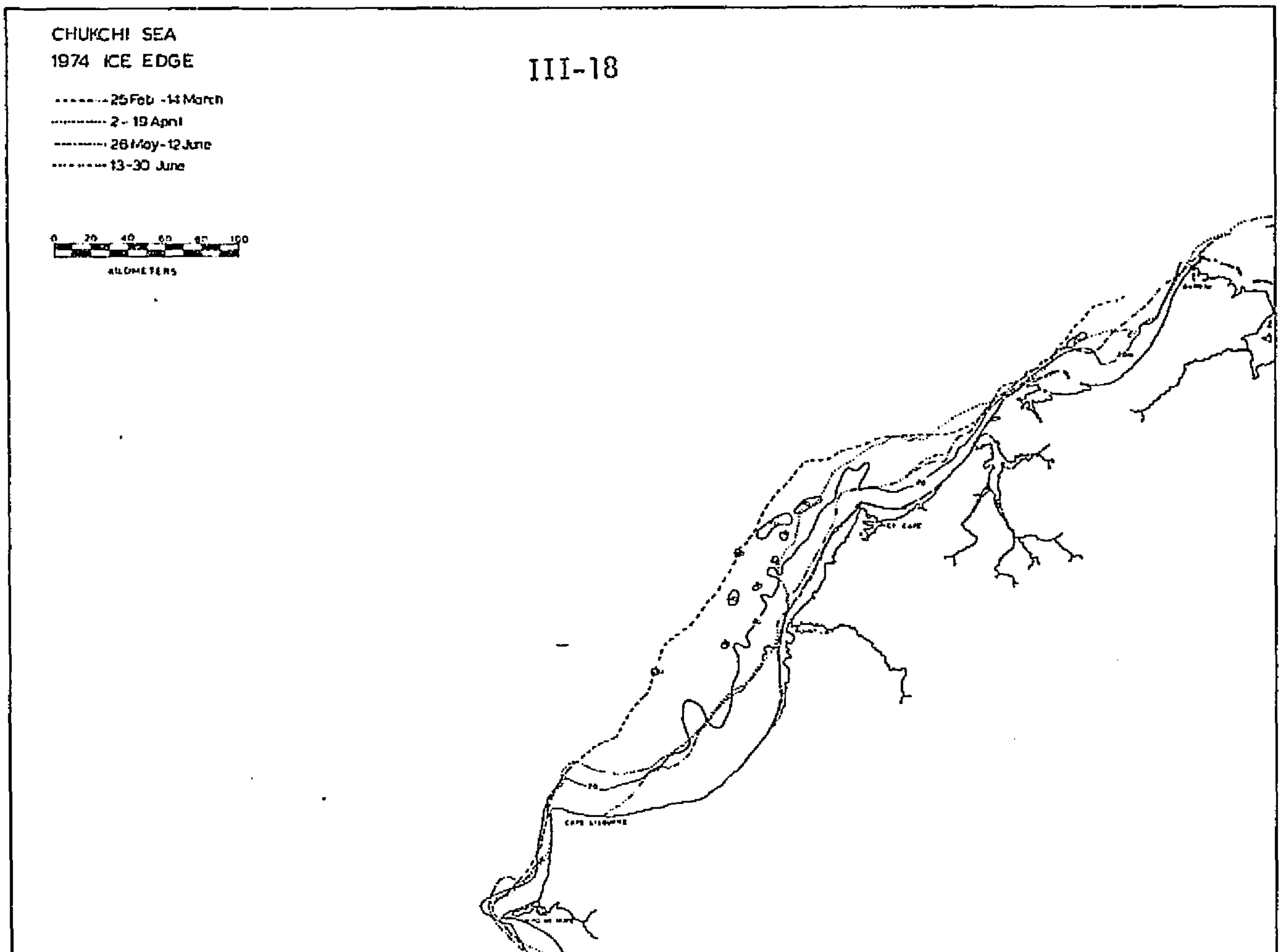
III-13


BEAUFORT SEA
1973-1977 RIDGE COMPOSITE
1973
1974
1975
1976
1977
KILOMETERS

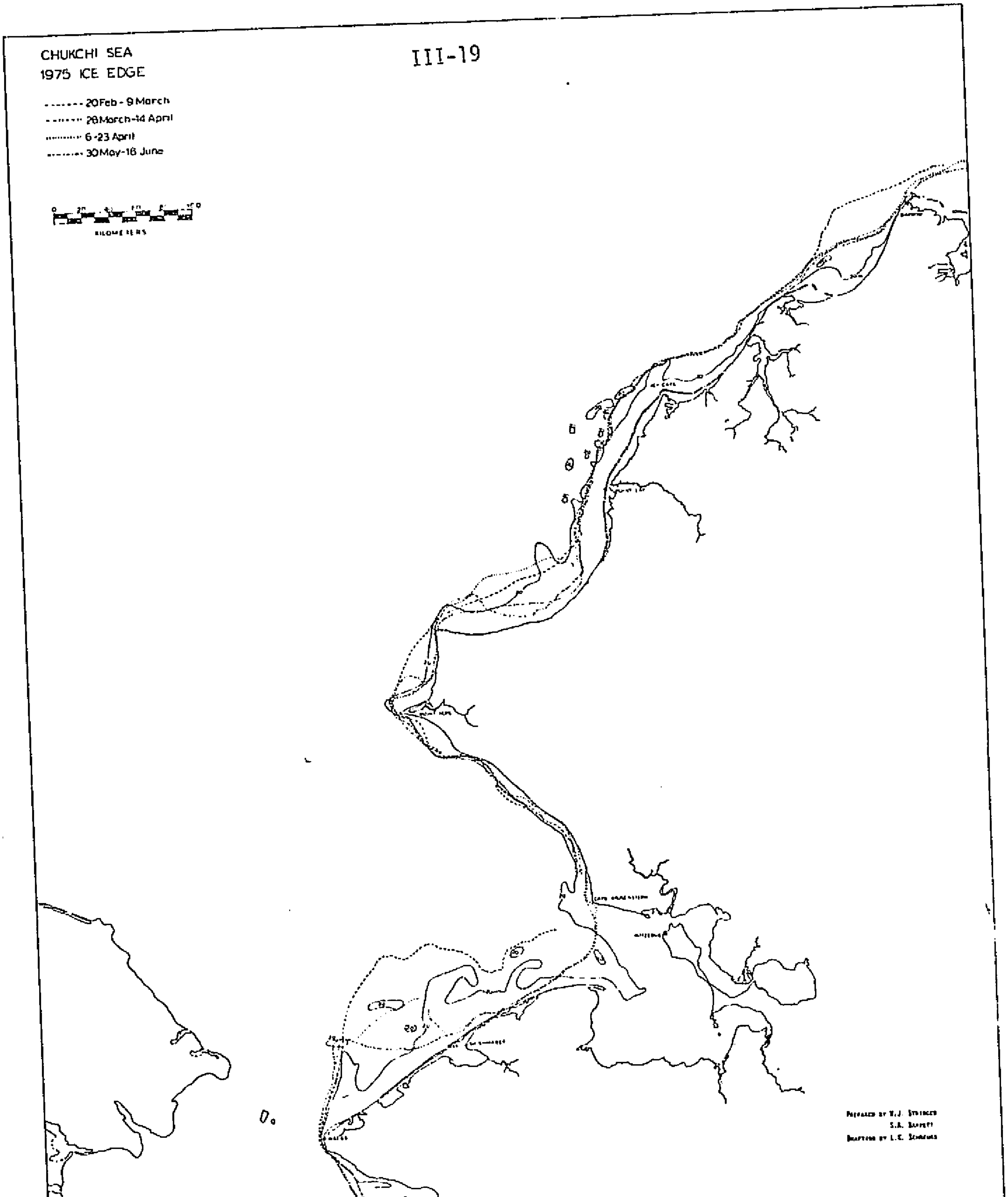

BEAUFORT SEA
ICE RIDGE DENSITY MAP
Little or no ridging
Light ridging
Medium ridging
Heavy ridging
SCALE 1:1,000,000
From 1973 through 1978 Landsat imagery
0 20 40 60 80 100
KILOMETERS
HARRISON BAY
CAMDEN BAY
Prepared by W.J. Stringer
S.A. Barrett


BEAUFORT SEA
STATIONARY ICE
2 July 1973
3 July 1973
12 July 1974
14 July 1974
6 July & 18 JULY 1975
24 July 1976
2 August 1976
0 20 40 60 80 100
6 JULY 1975
3 JULY 1973
2 AUGUST 1976
14 JULY 1974
2 JULY 1973
18 JULY 1975
12 JULY 1974
24 JULY 1976

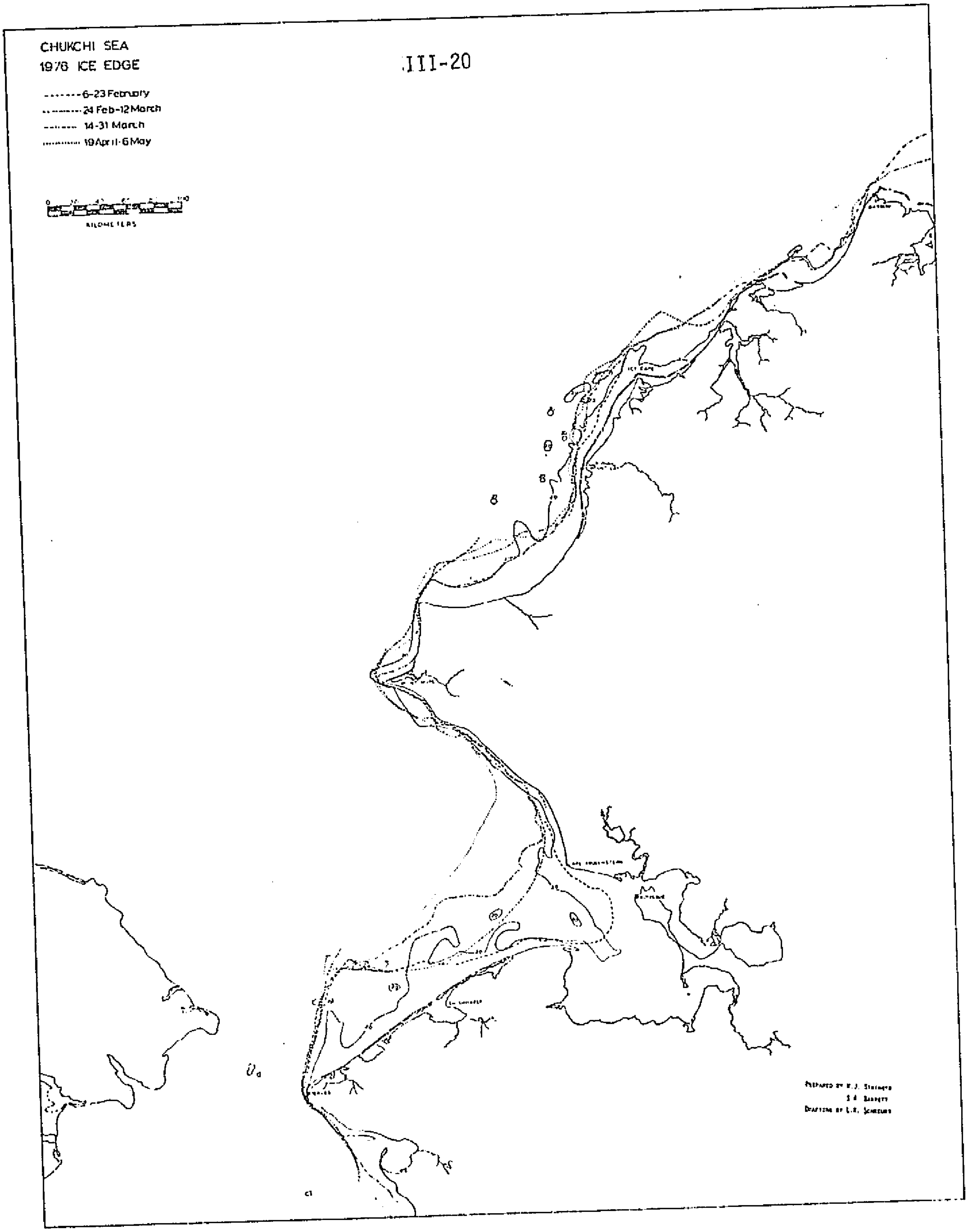

CHUKCHI SEA
1973 ICE EDGE
III-17
2-19 March
7-24 April
31 May - 17 June
KILOMETERS
BARROW
ICY CAPE
POINT LAY
CAPE LISBURNE
POINT HOPE
CAPE KRUSENSTERN
KOTZEBUE
SHISHMAREF
WALES


CHUKCHI SEA
1974 ICE EDGE
III-18
25 Feb -14 March
2 - 19 April
26 May-12 June
13-30 June
0 20 40 60 80 100
KILOMETERS
CAPE LISBURNE

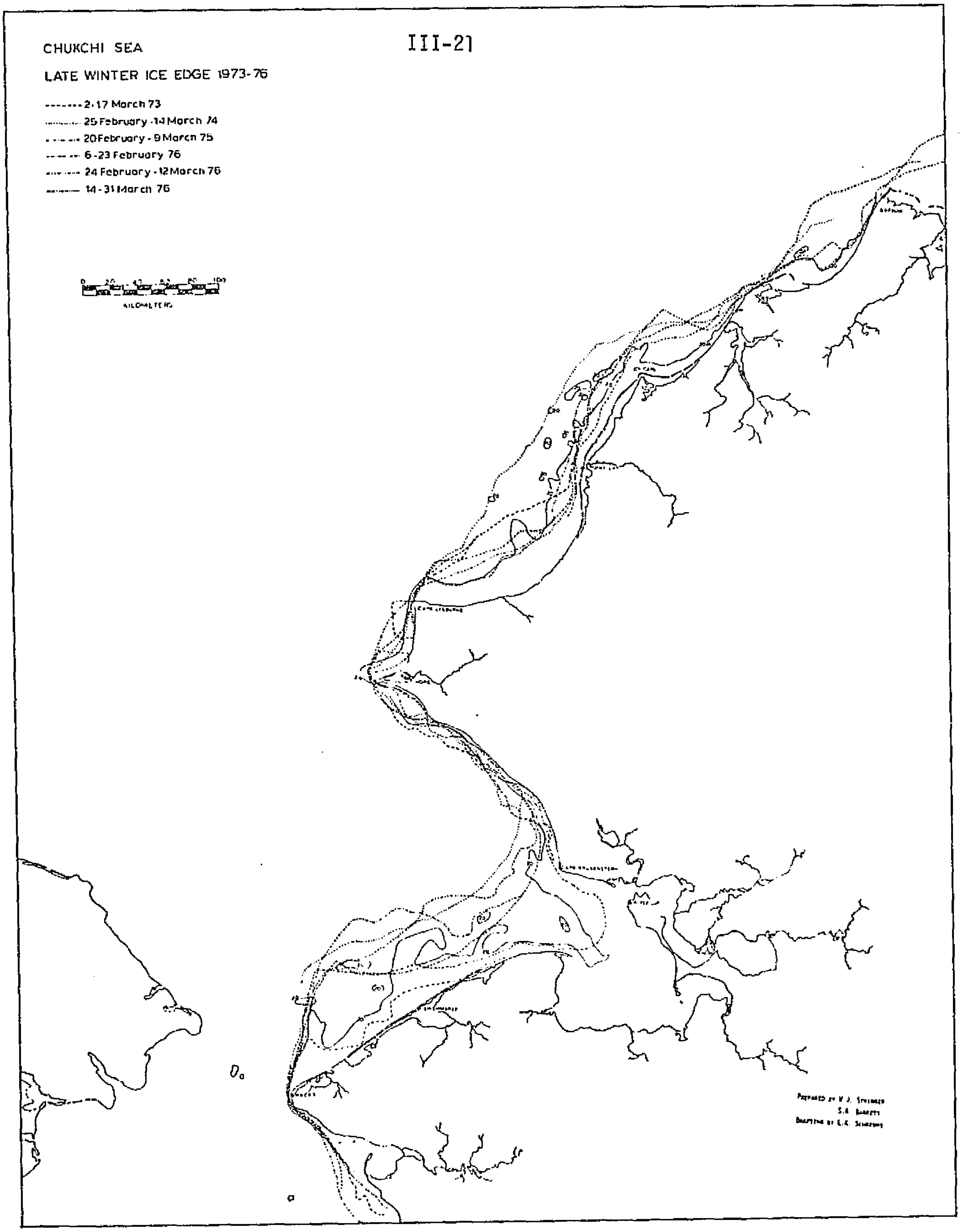
III-19

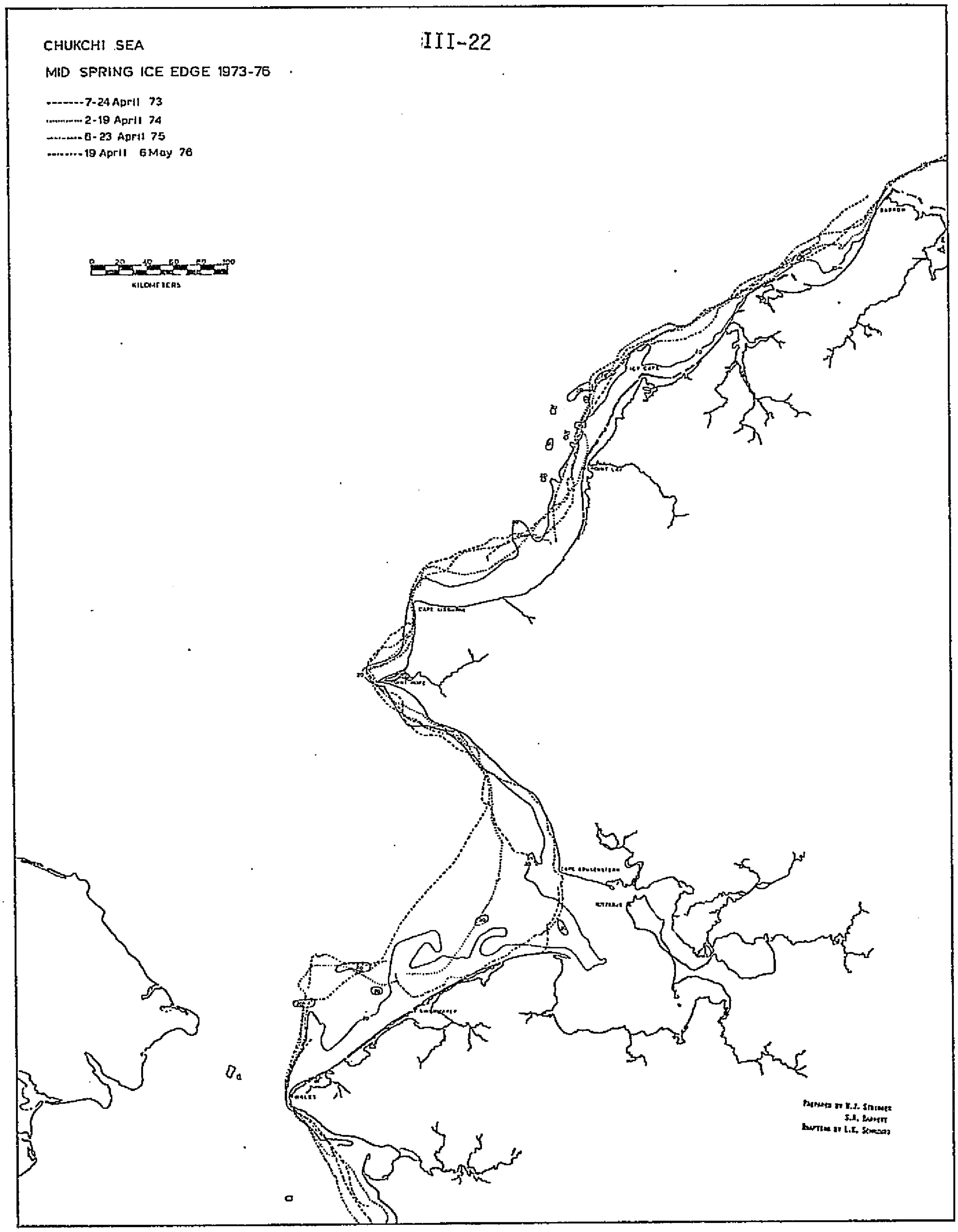

CHUKCHI SEA
1975 ICE EDGE
20Feb - 9 March
28March-14 April
6-23 April
30May-16 June
KILOMETERS

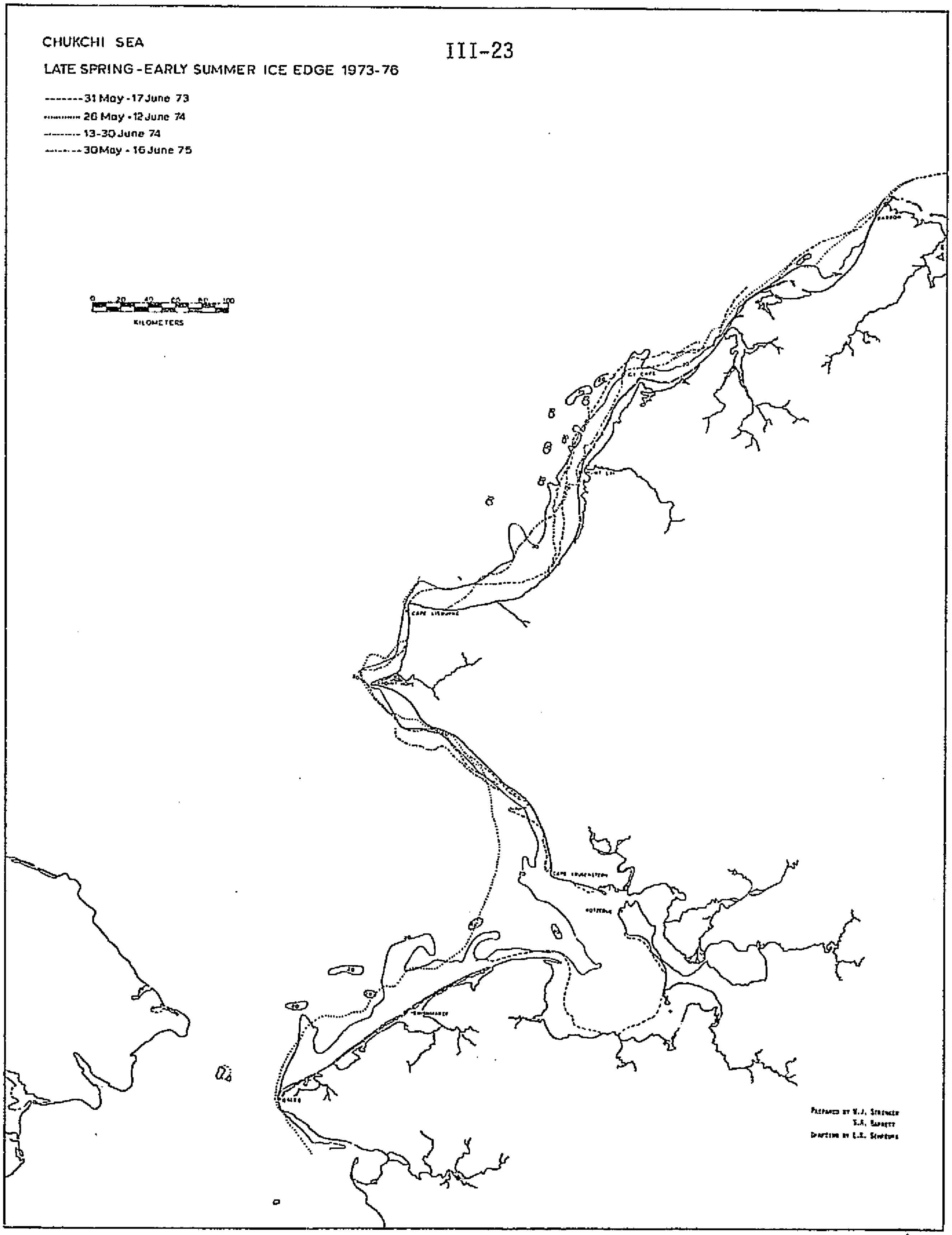
III-20


CHUKCHI SEA
1976 ICE EDGE
6-23 February
24 Feb-12 March
14-31 March
19 April-6 May
KILOMETERS

III-21


CHUKCHI SEA
LATE WINTER ICE EDGE 1973-76
2-17 March 73
25 February -14 March 74
20 February - 9 March 75
6-23 February 76
24 February - 12 March 76
14-31 March 76
KILOMETERS


III-22
CHUKCHI SEA
MID SPRING ICE EDGE 1973-76
7-24 April 73
2-19 April 74
8-23 April 75
19 April 6 May 76
KILOMETERS

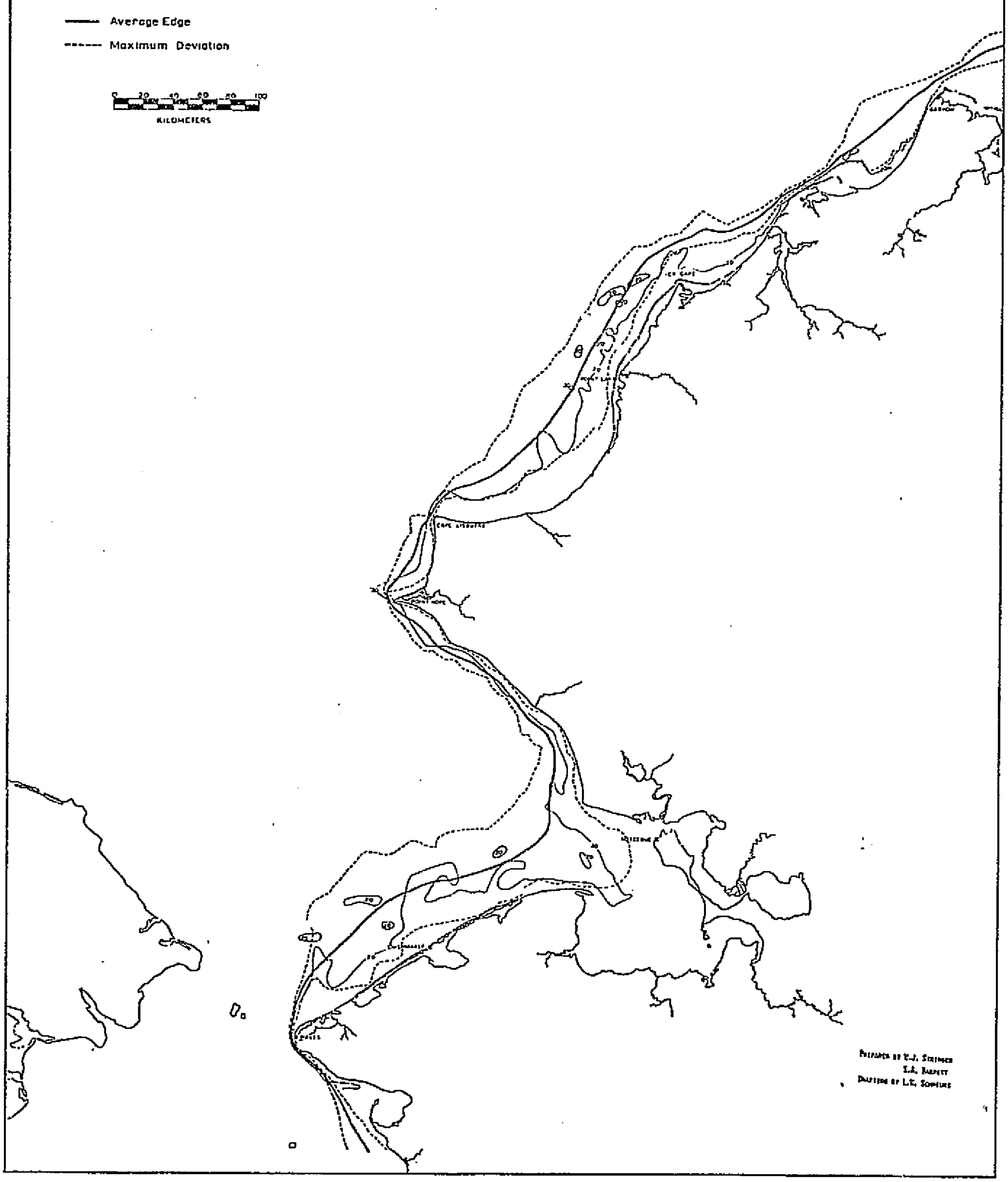

CHUKCHI SEA
LATE SPRING - EARLY SUMMER ICE EDGE 1973-76
III-23
31 May - 17 June 73
26 May - 12 June 74
13-30 June 74
30 May - 16 June 75
0 20 40 60 80 100
KILOMETERS

CHUKCHI SEA

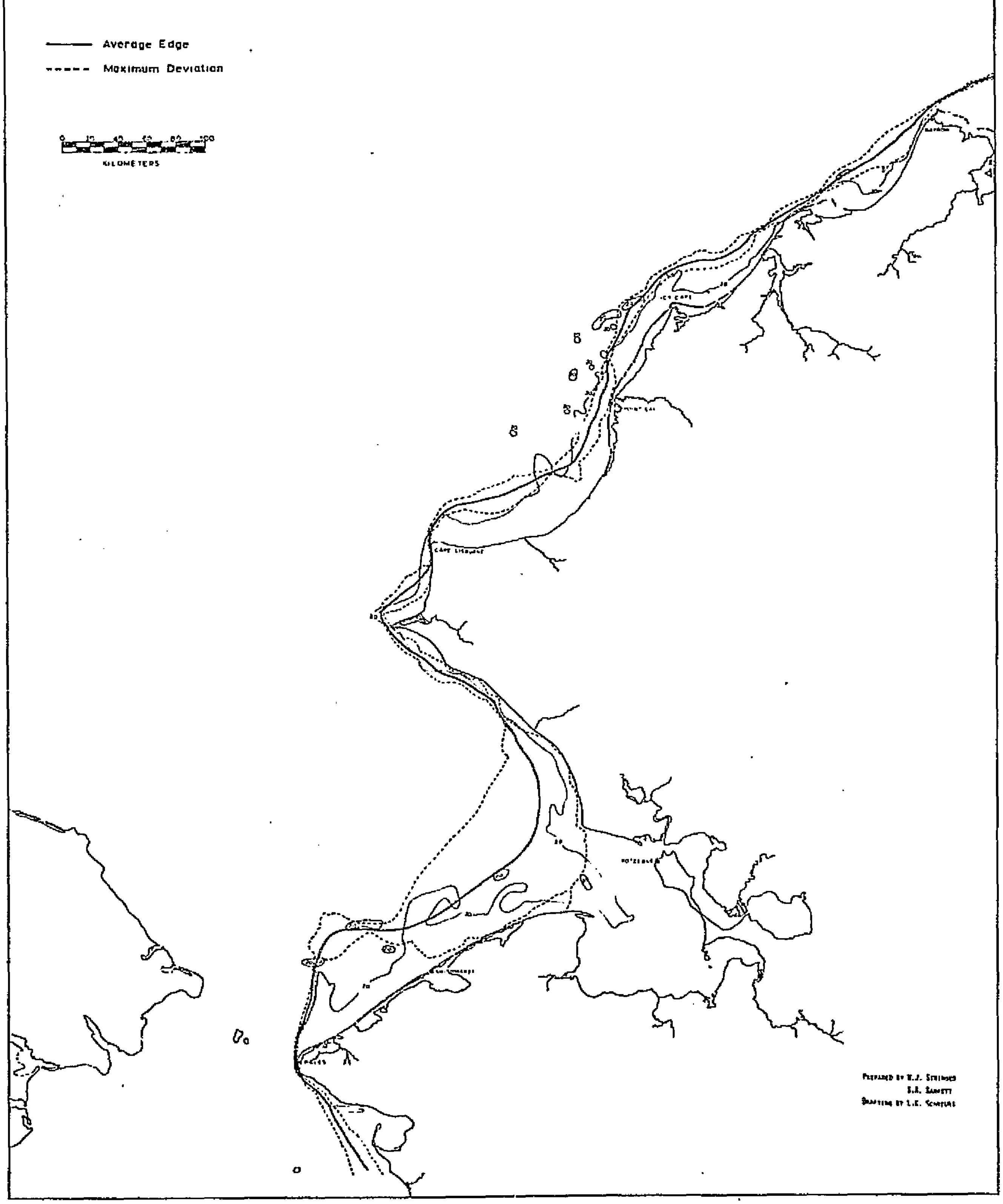
AVERAGE SEASONAL LATE-WINTER EDGE OF CONTIGUOUS ICE

1973-76

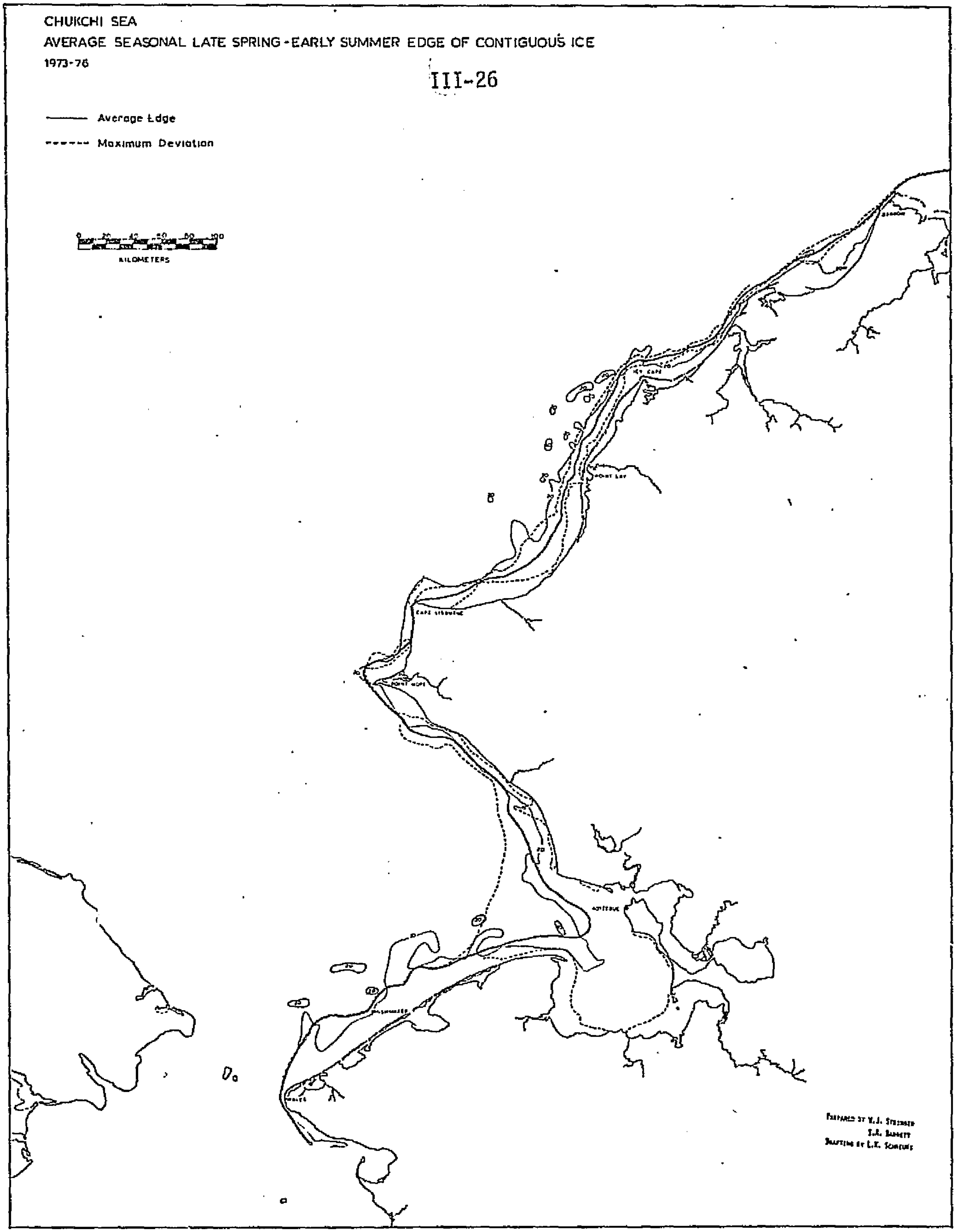
III-24



III-25



CHUKCHI SEA
AVERAGE SEASONAL MID-SPRING EDGE OF CONTIGUOUS ICE
1973-76



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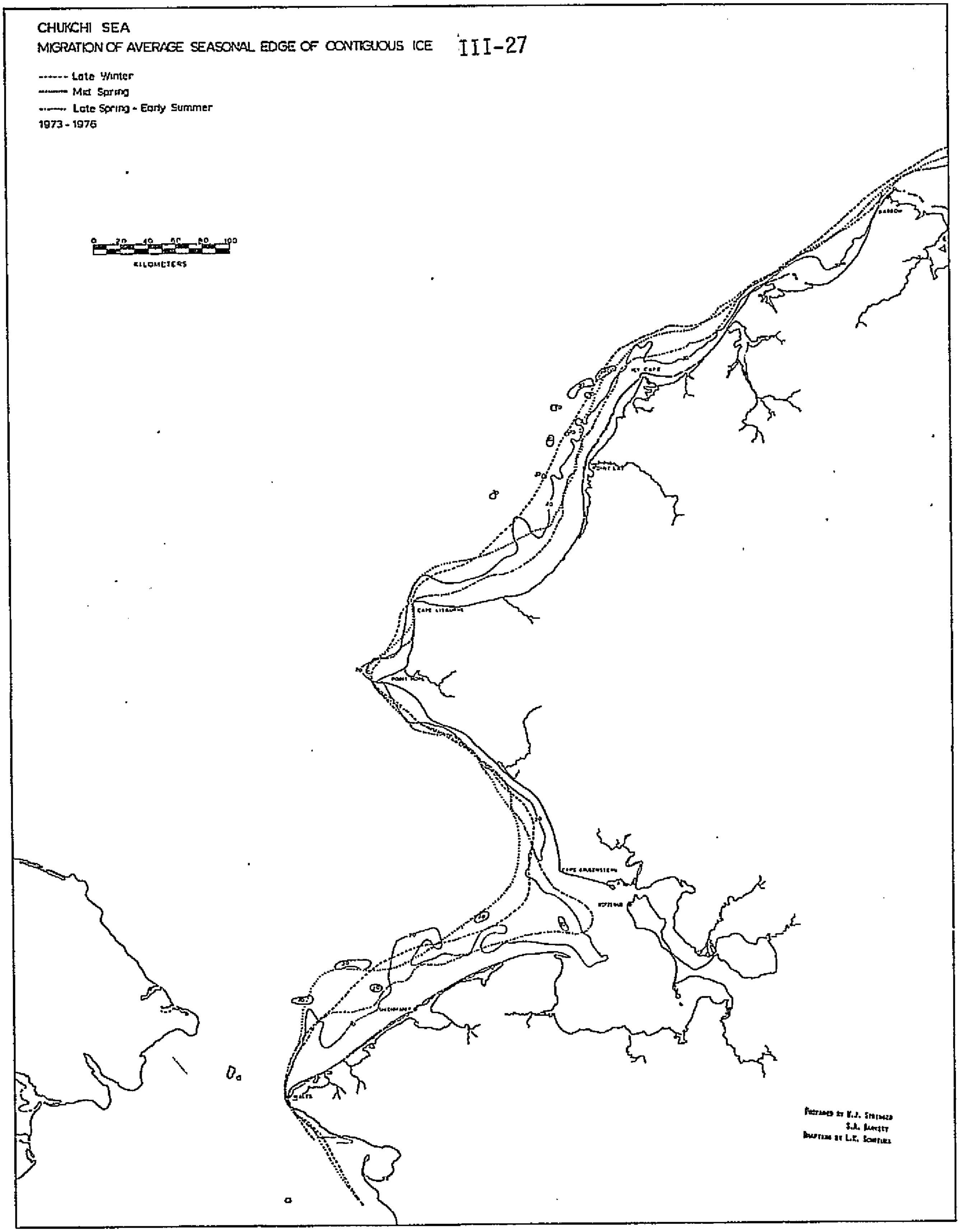
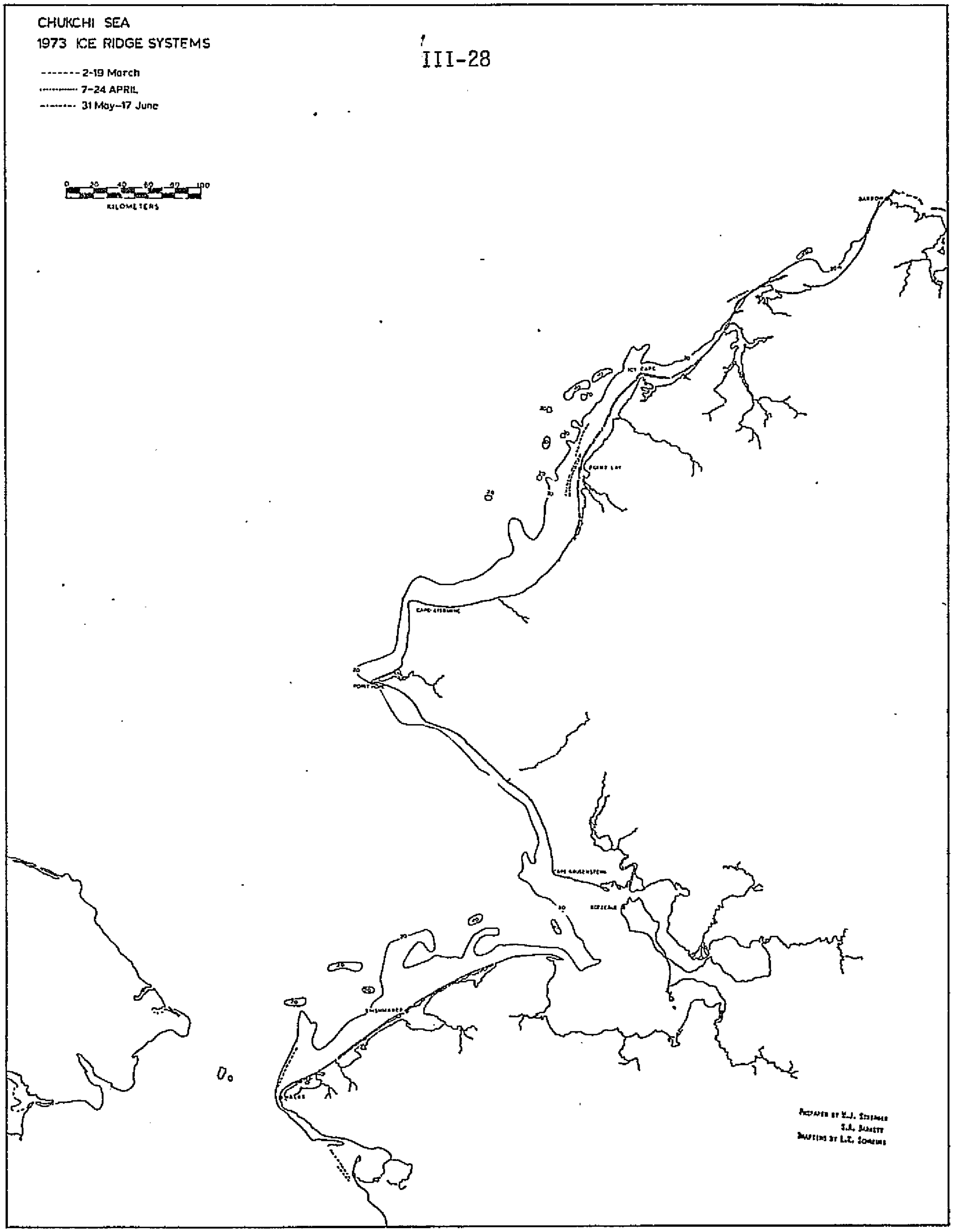
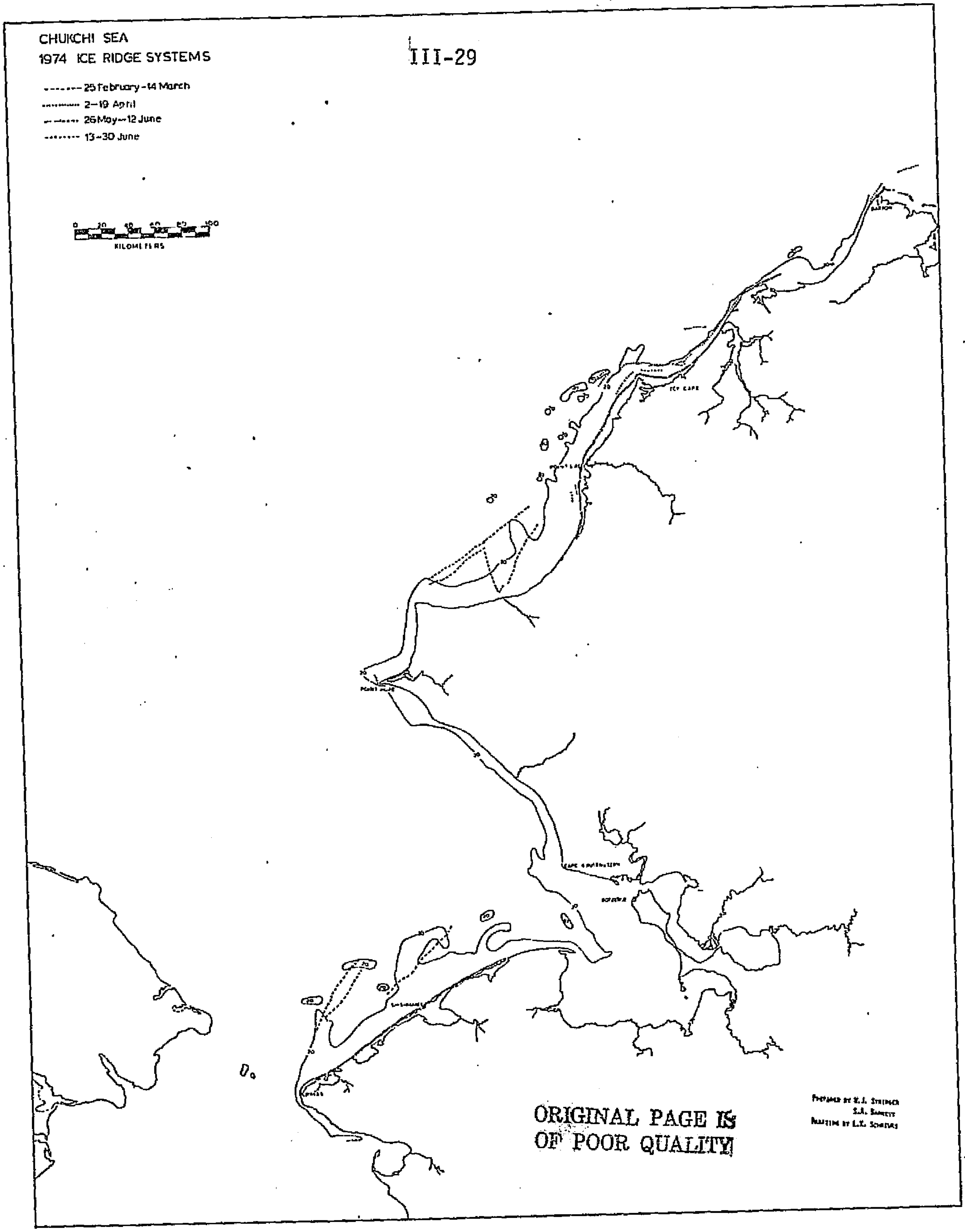
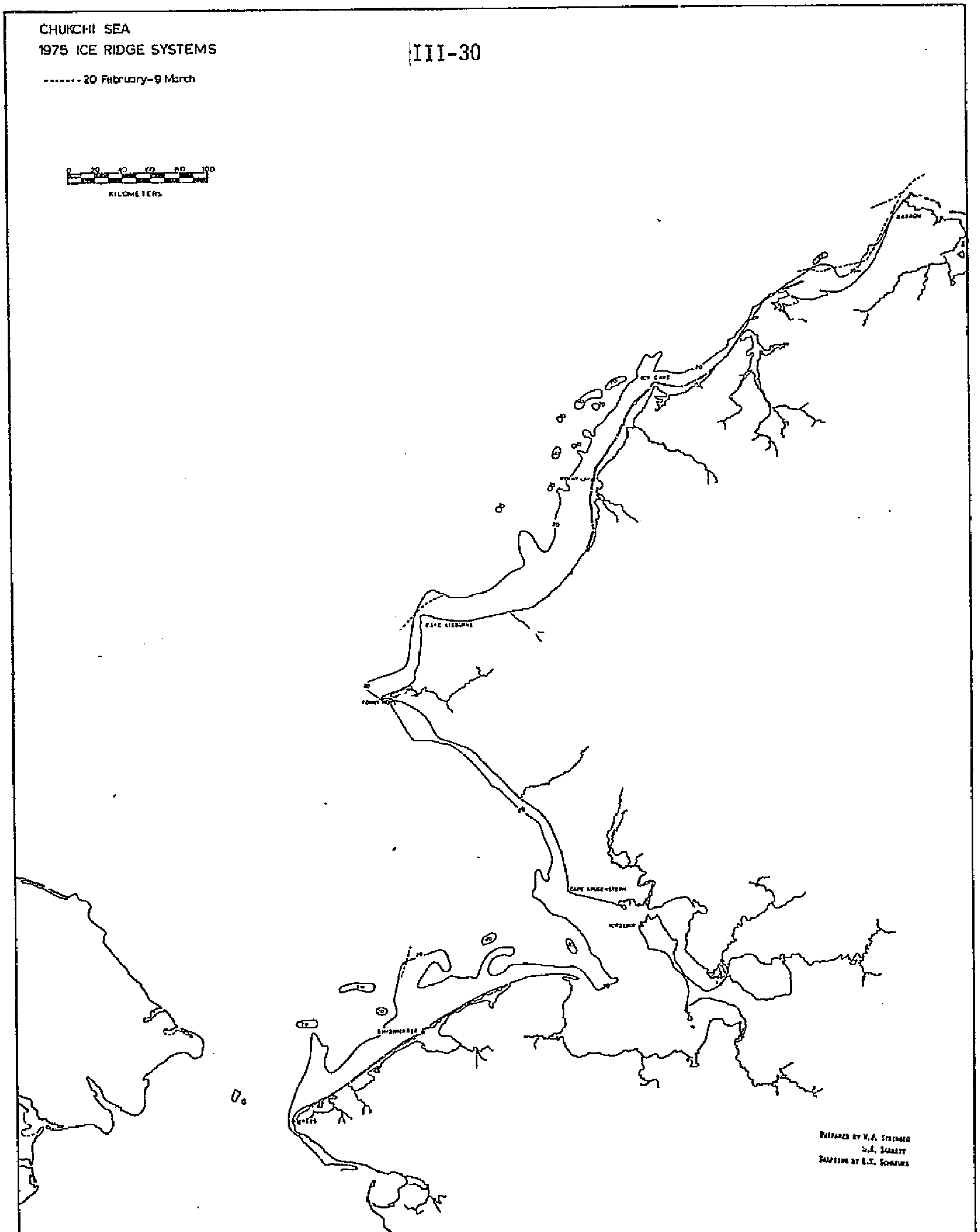

CHUKCHI SEA
MIGRATION OF AVERAGE SEASONAL EDGE OF CONTIGUOUS ICE
III-27
Late Winter
Mid Spring
Late Spring - Early Summer
1973 - 1976
0 20 40 60 80 100
KILOMETERS



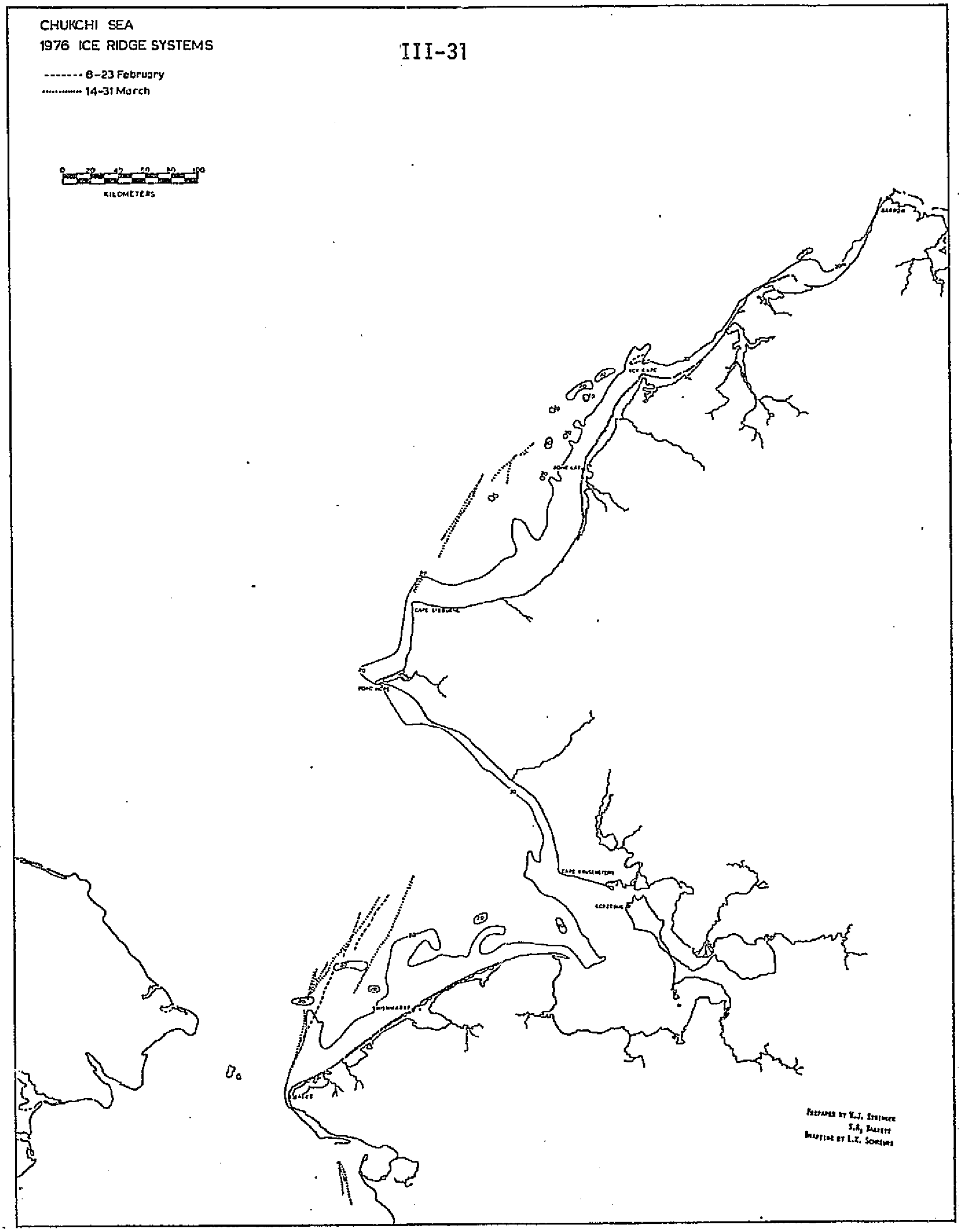
CHUKCHI SEA
1973 ICE RIDGE SYSTEMS
2-19 March
7-24 APRIL
31 May-17 June
III-28
0 20 40 60 80 100
KILOMETERS


CHUKCHI SEA
1974 ICE RIDGE SYSTEMS
25 February - 14 March
2-19 April
26 May - 12 June
13-30 June
0 20 40 60 80 100
KILOMETERS

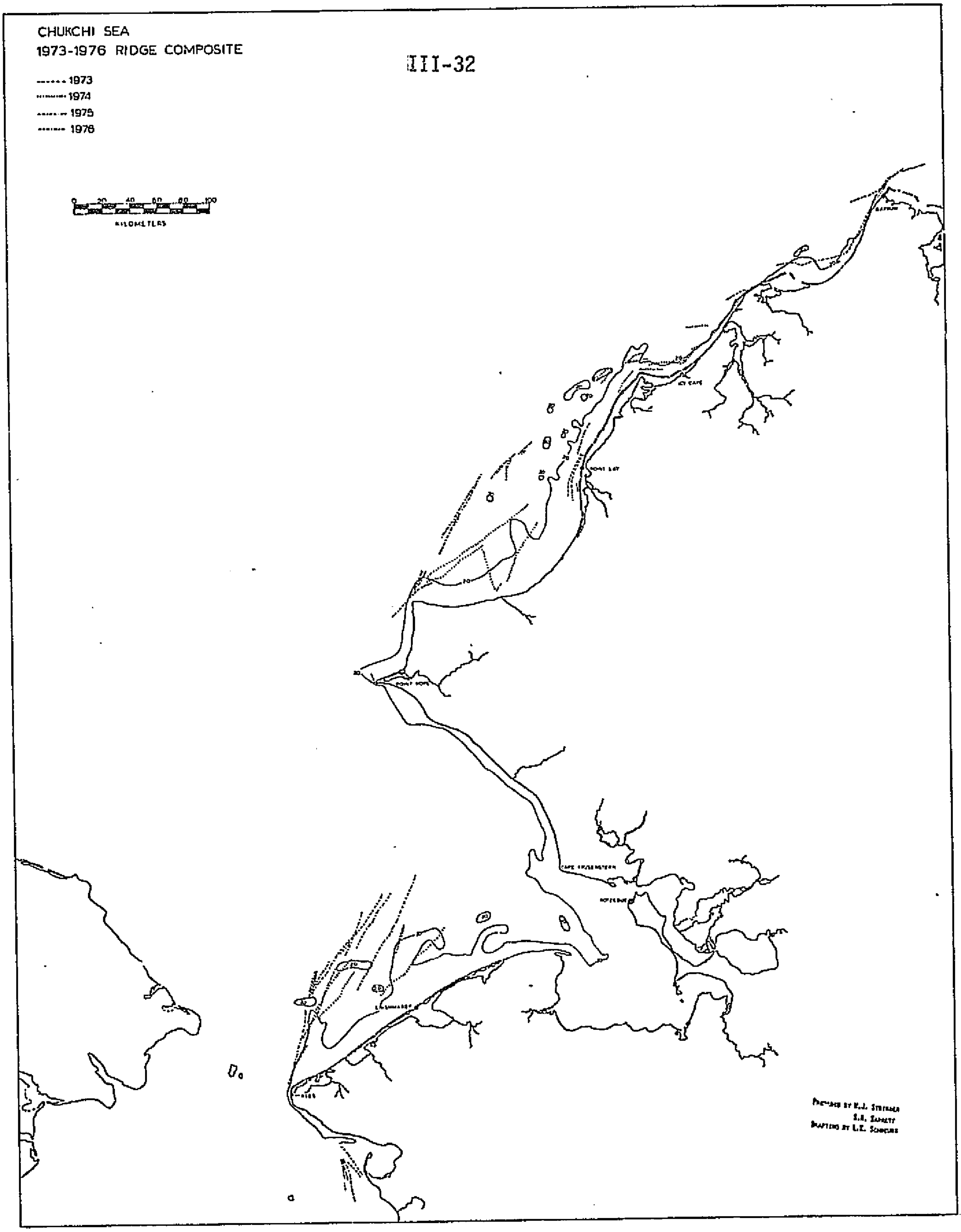

CHUKCHI SEA
1975 ICE RIDGE SYSTEMS
------- 20 February–9 March
0 20 40 60 80 100
KILOMETERS

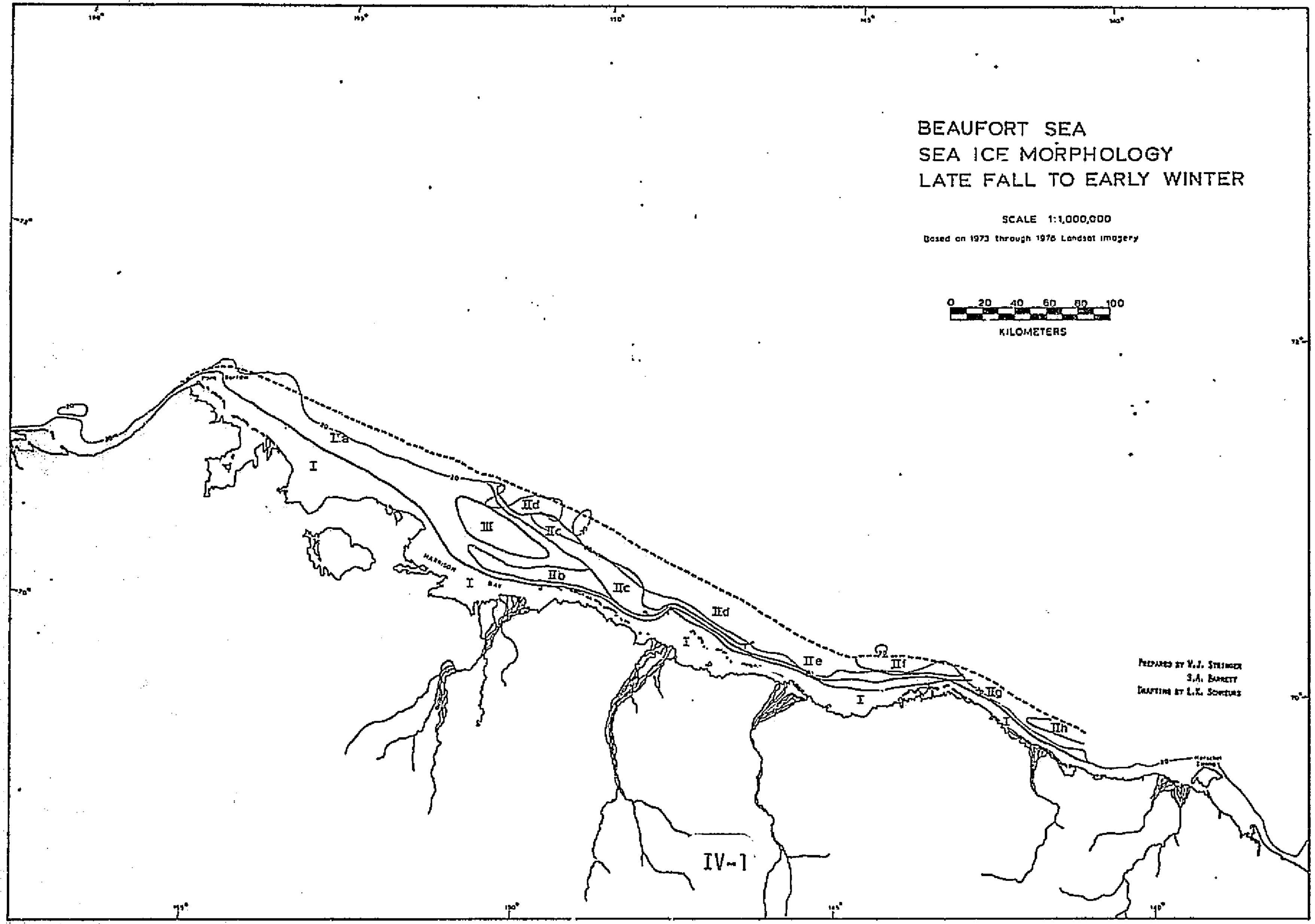
III-30

III-31

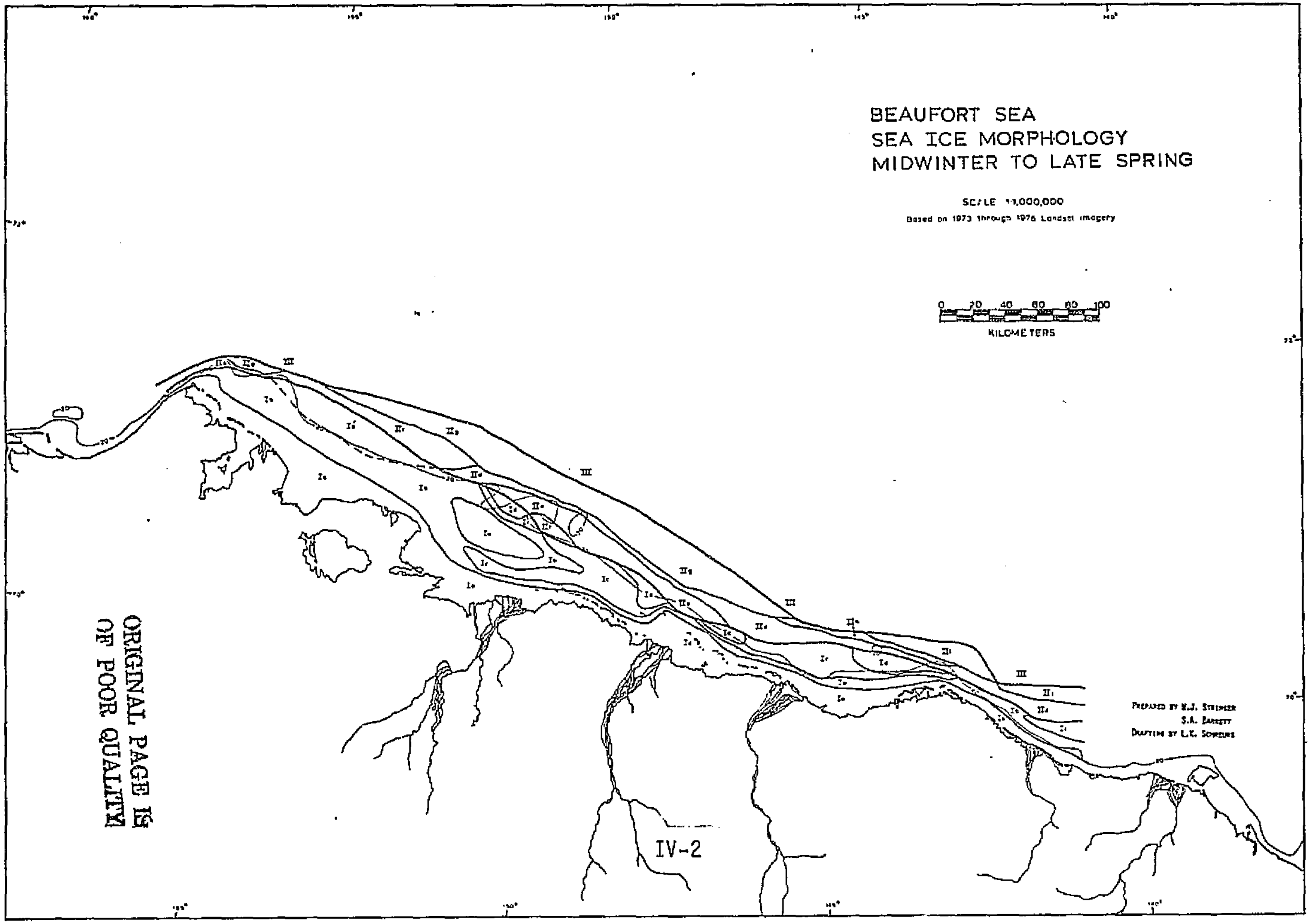

CHUKCHI SEA
1976 ICE RIDGE SYSTEMS
6–23 February
14–31 March
KILOMETERS

III-32

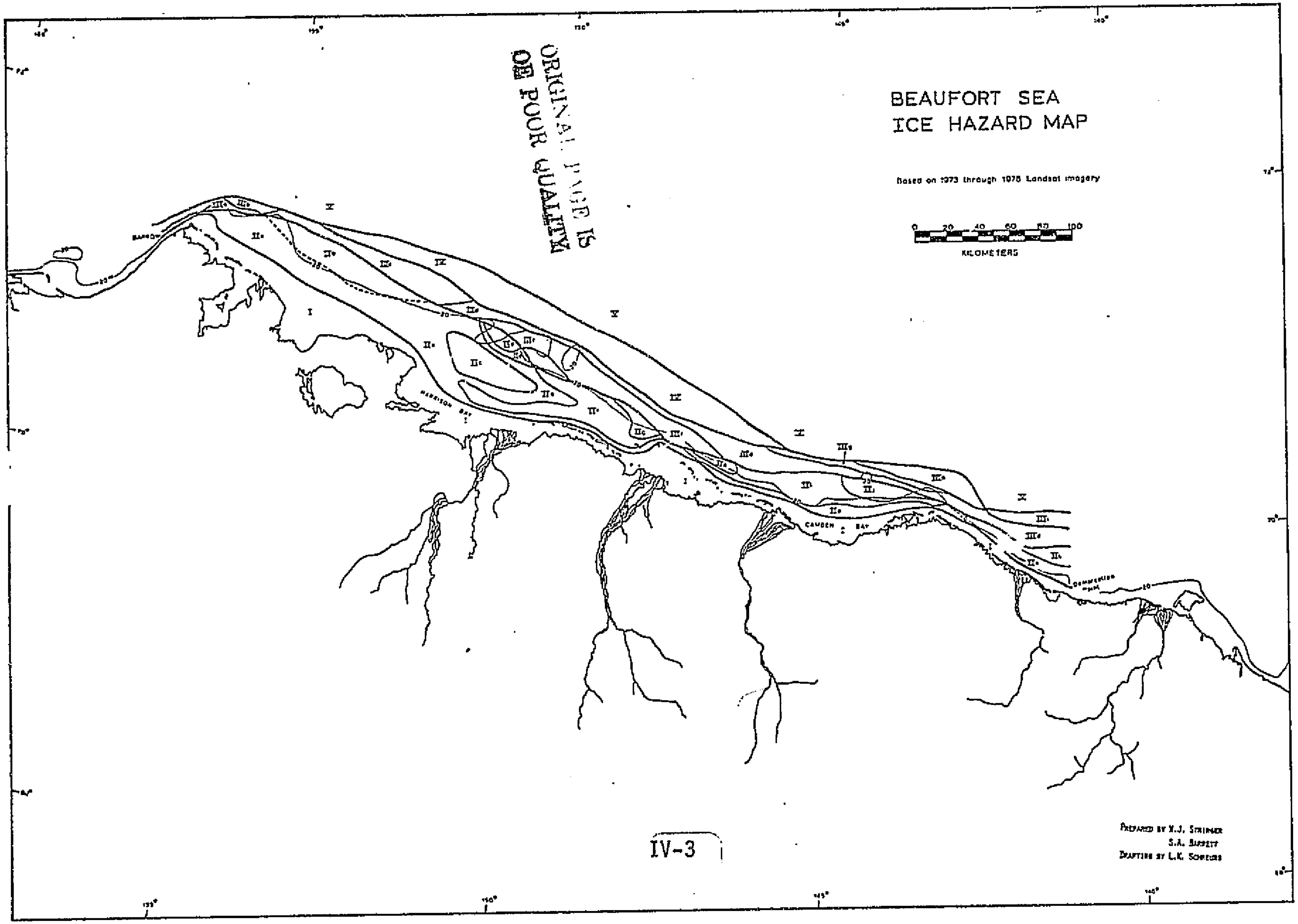

CHUKCHI SEA
1973-1976 RIDGE COMPOSITE
1973
1974
1975
1976
0 20 40 60 80 100
KILOMETERS


BEAUFORT SEA
SEA ICE MORPHOLOGY
LATE FALL TO EARLY WINTER
SCALE 1:1,000,000
Based on 1973 through 1976 Landsat imagery
0 20 40 60 80 100
KILOMETERS
PREPARED BY W.J. STRINGER
S.A. BARRETT
DRAFTING BY L.K. SCHREURS
I
IIa
IIb
IIc
IId
IIe
IIf
IIg
IIh
III
HARRISON BAY

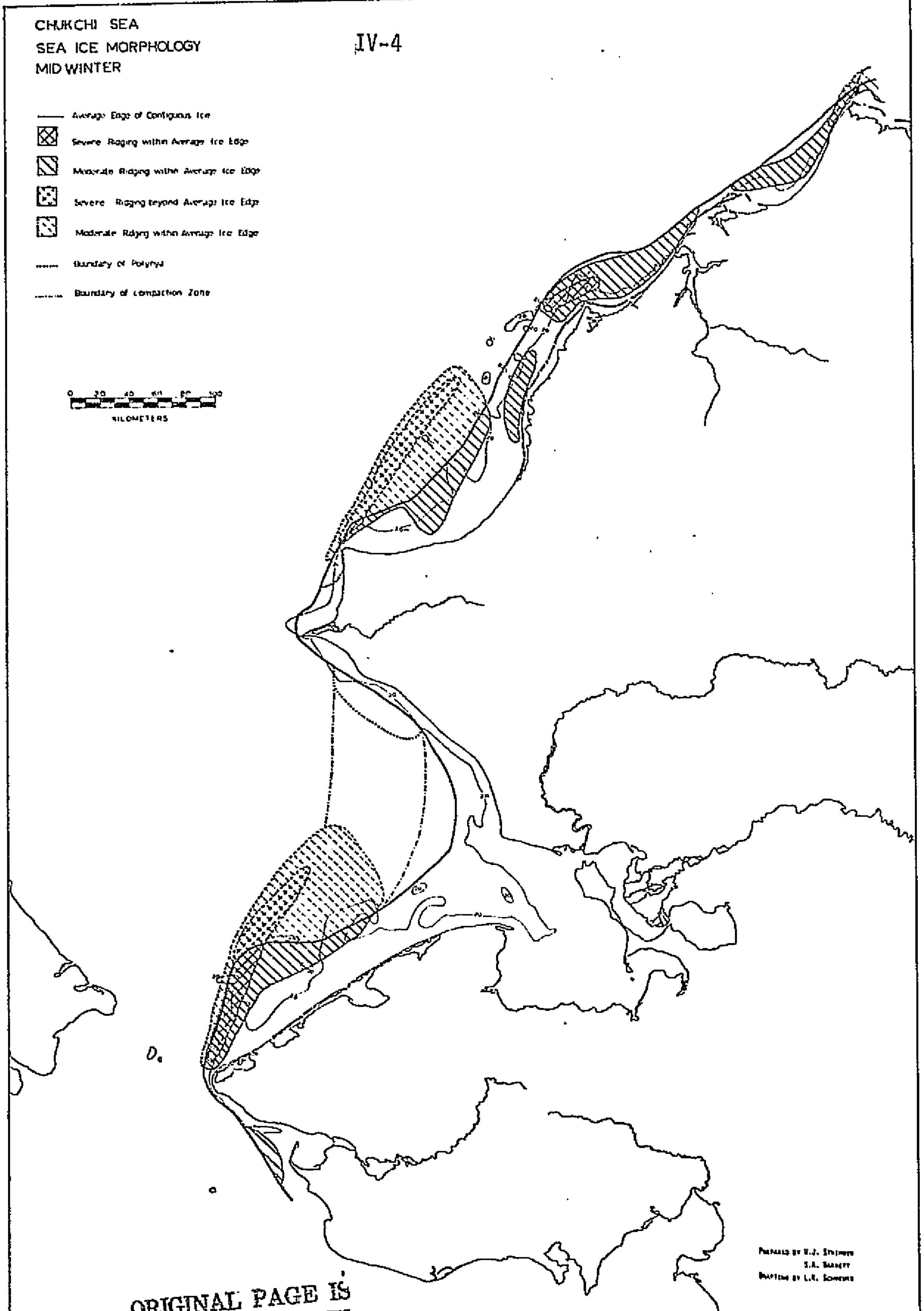
IV-1

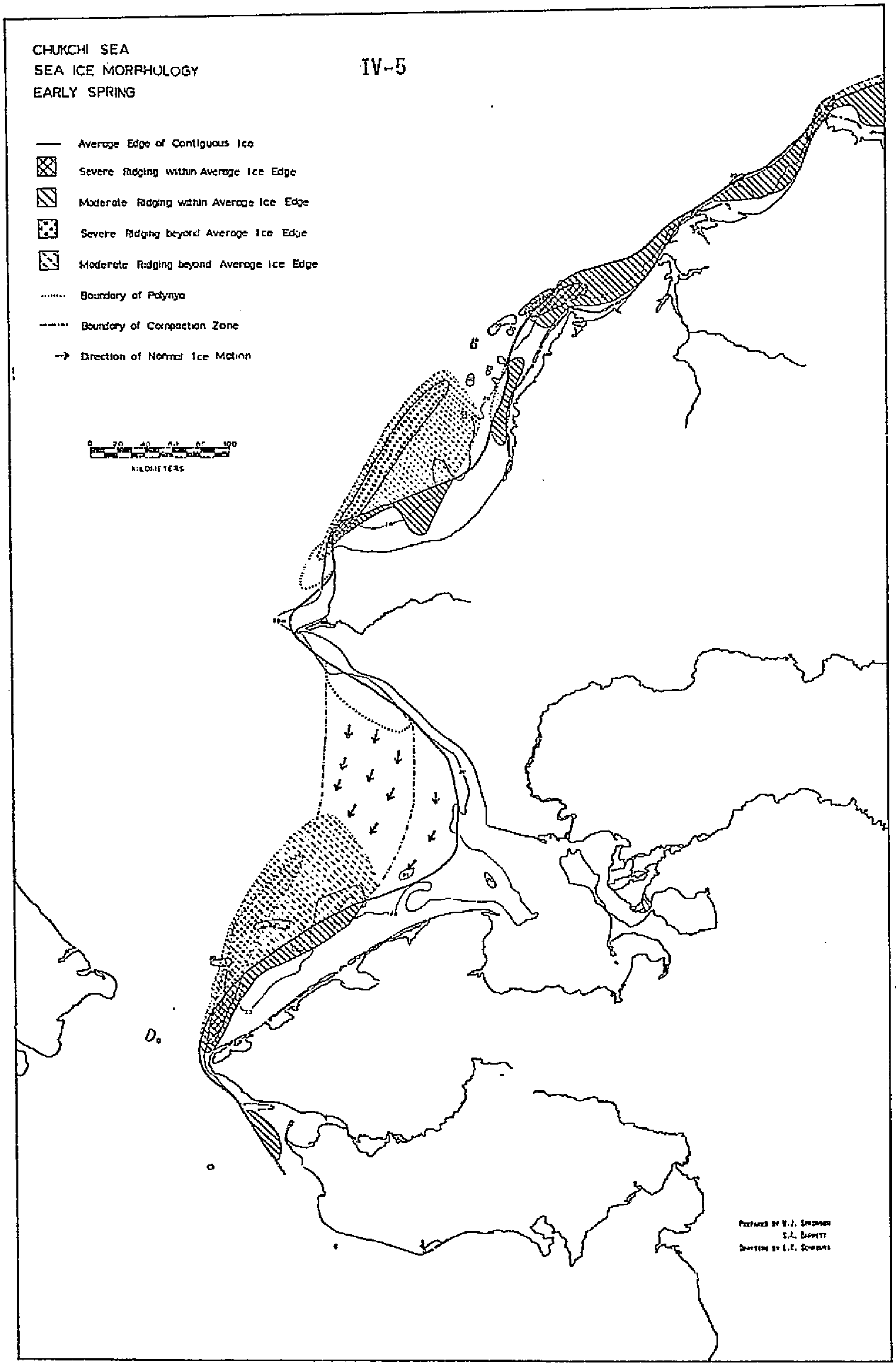

BEAUFORT SEA
SEA ICE MORPHOLOGY
MIDWINTER TO LATE SPRING
KILOMETERS

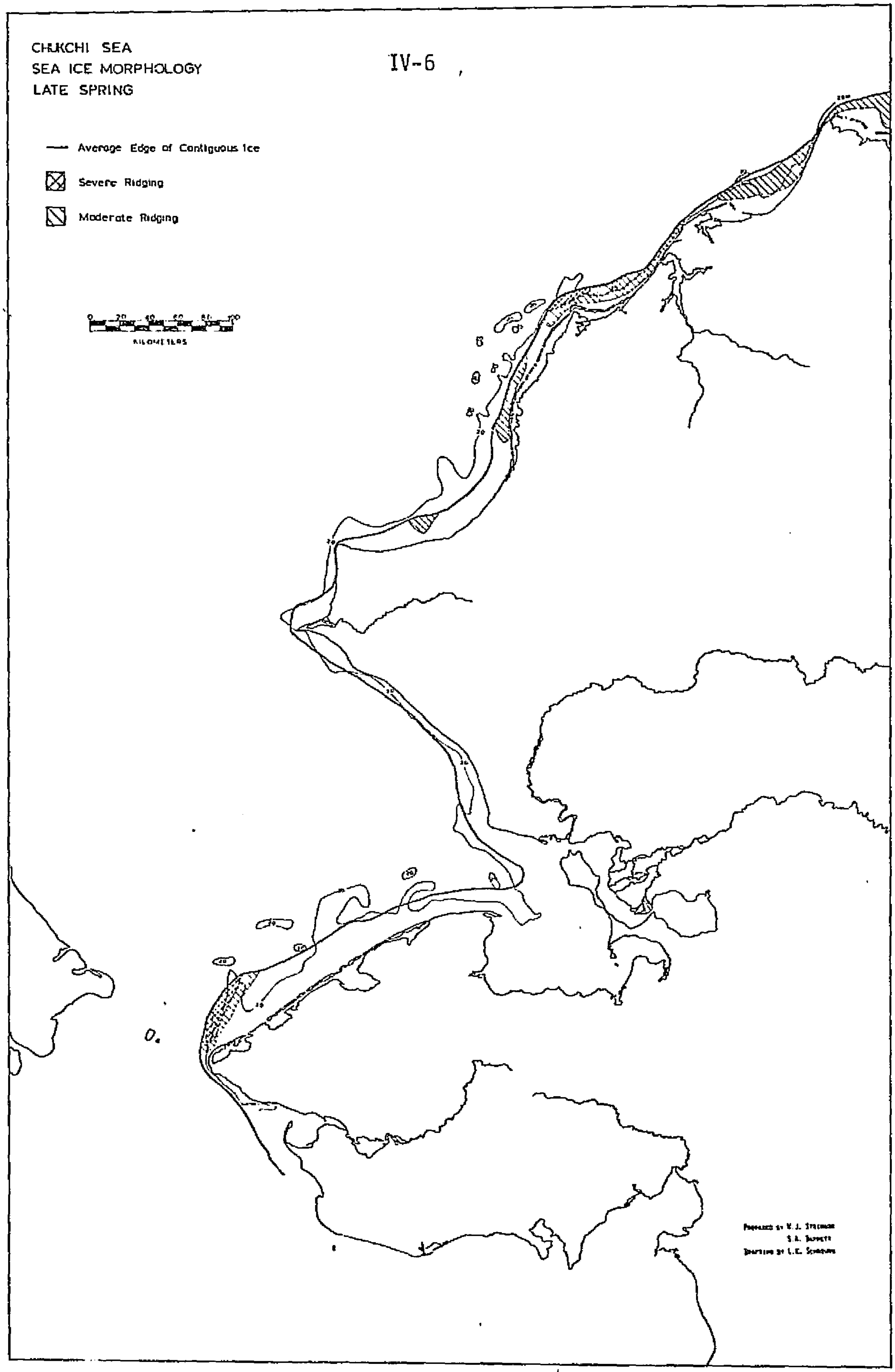
IV-2

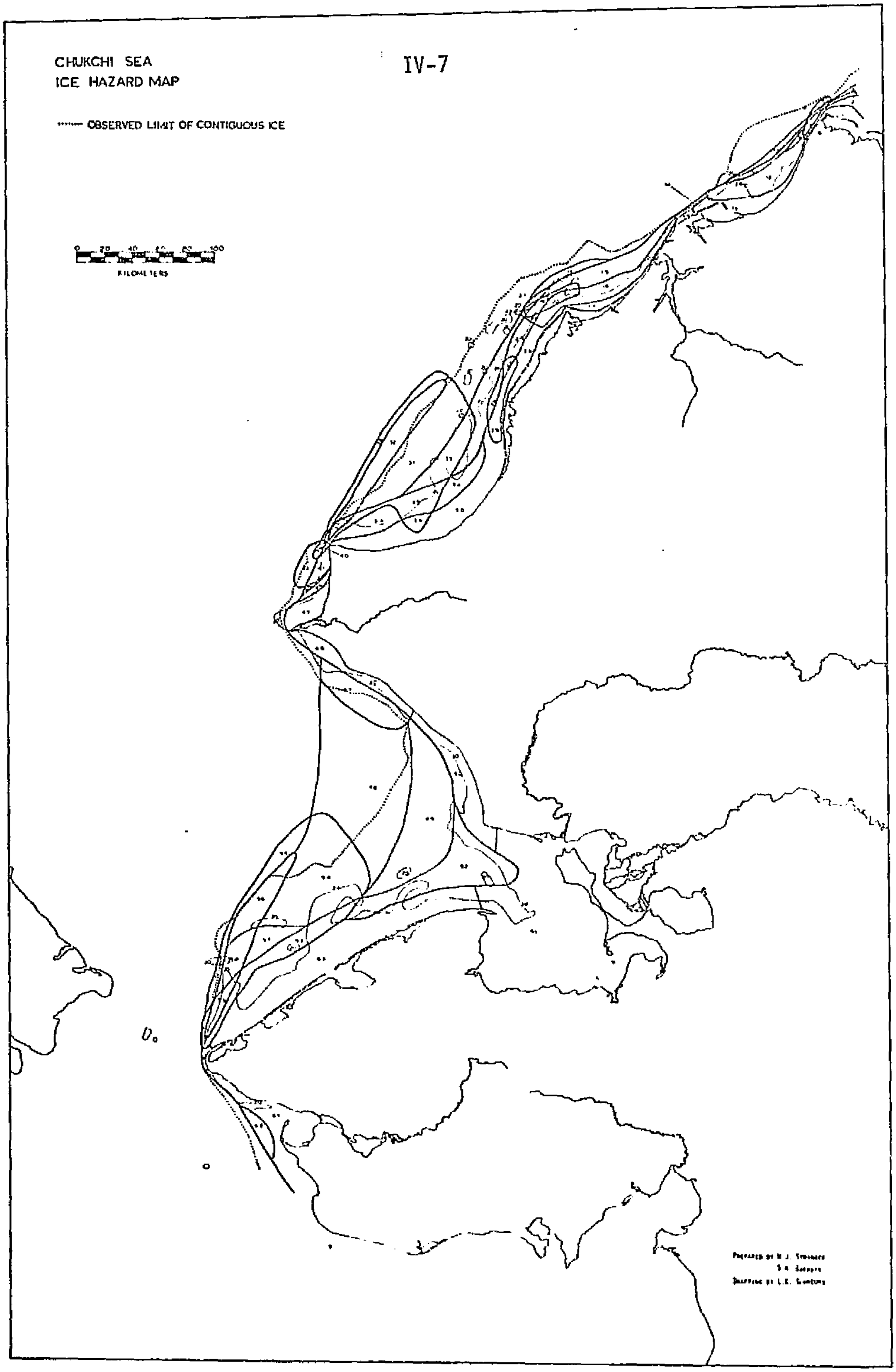

BEAUFORT SEA
ICE HAZARD MAP
Based on 1973 through 1975 Landsat imagery
0 20 40 60 80 100
KILOMETERS
CAMDEN BAY
HARRISON BAY

200


CHUKCHI SEA
SEA ICE MORPHOLOGY
MID WINTER
IV-4
Average Edge of Contiguous Ice
Severe Ridging within Average Ice Edge
Moderate Ridging within Average Ice Edge
Severe Ridging beyond Average Ice Edge
Moderate Ridging within Average Ice Edge
Boundary of Polynya
Boundary of compaction Zone
0 20 40 60 80 100
KILOMETERS


CHUKCHI SEA
SEA ICE MORPHOLOGY
EARLY SPRING
IV-5
Average Edge of Contiguous Ice
Severe Ridging within Average Ice Edge
Moderate Ridging within Average Ice Edge
Severe Ridging beyond Average Ice Edge
Moderate Ridging beyond Average Ice Edge
Boundary of Polynya
Boundary of Compaction Zone
Direction of Normal Ice Motion
KILOMETERS


CHUKCHI SEA
SEA ICE MORPHOLOGY
LATE SPRING
IV-6
Average Edge of Contiguous Ice
Severe Ridging
Moderate Ridging
0 20 40 60 80 100
KILOMETERS



CHUKCHI SEA
ICE HAZARD MAP
IV-7
OBSERVED LIMIT OF CONTIGUOUS ICE
0 20 40 60 80 100
KILOMETERS